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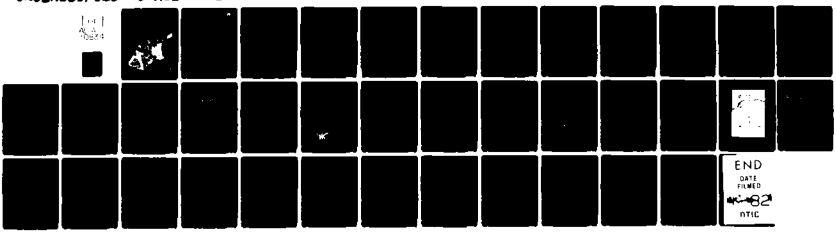

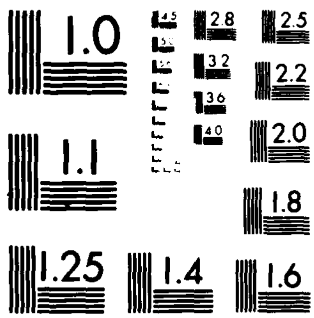

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Subsea trenching in the Arctic

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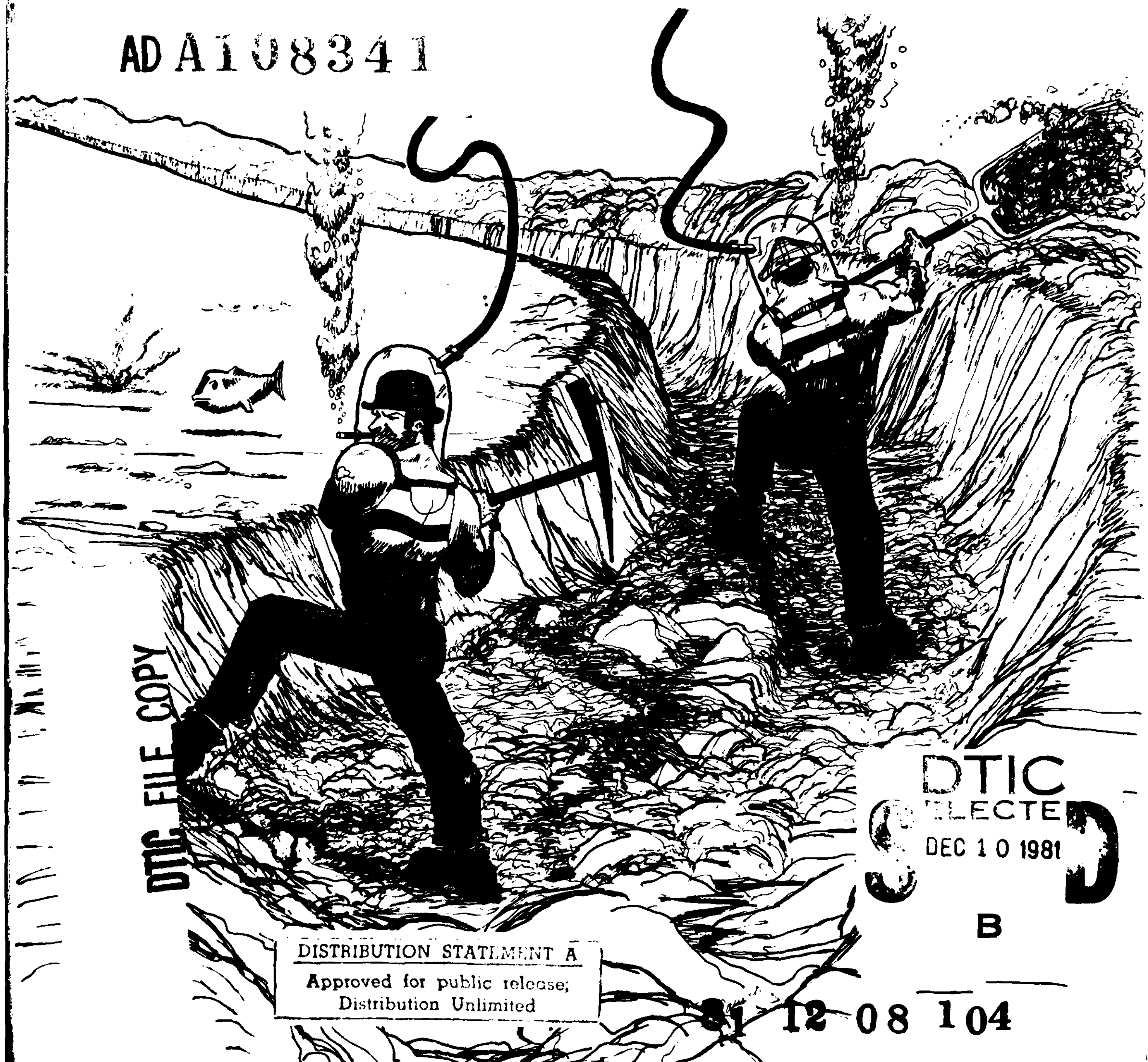

CRREL Report 81-17

Subsea trenching in the Arctic

Malcolm Mellor

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Environmental conditions are described for the continental shelf of the western Arctic, and for the shelf of Labrador and Newfoundland. Special emphasis is given to the gouging of bottom sediments by ice pressure ridges and icebergs, and an approach to systematic risk analysis is outlined. Protection of subsea pipelines and cables by trenching and direct embedment is discussed, touching on burial depth, degree of protection, and environmental impact. Conventional land techniques can be adapted for trenching across the beach and through the shallows, but in deeper water special equipment is required. The devices discussed include hydraulic dredges, submarine dredges, plows, rippers, water jets, disc saws and wheel ditchers, ladder trenchers and chain saws, routers and slot millers, ladder dredges, vibratory and percussive machines, and blasting systems. Consideration is given to the relative merits of working with seabed vehicles, or alternatively with direct surface support from vessels or from the sea ice.

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PREFACE

This report was prepared by Dr. Malcolm Mellor, Research Physical Scientist, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was performed for the U.S. Navy Civil Engineering Laboratory (Work Request N6830580WR00186).

The author acknowledges the many people who have generously provided illustrations, information and advice for this paper, especially colleagues at CRREL and the USN CEL, and engineers at British Oceanics, Brown and Root, Harmstorf, Land and Marine Engineering (Royal Bos Kalis Westminster), Offshore Innovation Engineering (Heerema), R.J. Brown, Tecnomare, and Volker Stevin Dredging/Aveco (Royal Volker Stevin).

Technical review of the report was performed by Paul V. Sellmann of CRREL.

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INTRODUCTION

In arctic and subarctic waters, much of the seabed is gouged by sea ice or icebergs, and shorelines are subject to ice action. Undersea cables and pipelines therefore need protection. Here we consider the problems of trenching and direct embedment of pipes and cables, passing over the alternative of direct burial by placement of fill, riprap, or fabricated covers. Important questions include the following: 1) What kind of conditions prevail in arctic and subarctic waters? 2) What are the characteristics of ice gouges? 3) How does permafrost affect the seabed? 4) How deep should pipes and cables be buried? 5) What techniques and equipment are suitable for work in northern waters?

Ice gouging and ice action on shores are widespread in circumpolar regions, and even in some waters of the temperate regions, including the Great Lakes. However, for present purposes we examine the conditions in two representative areas: 1) the shallow continental shelf of the western Arctic, where gouging is mainly by sea ice pressure ridges, and 2) the continental shelf of Labrador and Newfoundland, where there is serious gouging by icebergs. More detailed descriptions of the areas, with references, are given in the Appendix, and a few relevant points are summarized below.

THE WESTERN ARCTIC OF NORTH AMERICA

The continental shelf of the Beaufort and Chukchi Seas is shallow and flat, and most work is likely to be at depths not exceeding 50 m (160 ft). This means that 1) scuba or similar equipment can be used for much of the diving, 2) there are no great pressure problems for equipment, 3) power and control umbilicals can be short, 4) cables for towing and lifting can be short, and surface vessels can even reach down to the bottom with rigid booms.

Technically, much of the seabed is "permafrost," in that the temperature is below 0°C. However, beyond the 2-m isobath it is unlikely that there will be any significant ice bonding of the saline sediments within the layers penetrated by trenches. In the shallows (less than 2 m deep), and on the beach, the sediments freeze seasonally, and thus strength fluctuates considerably.

Over the whole area there is a discontinuous veneer of loose mud or sand, up to a few metres thick in places. This may be very weak, with shear strength less than 35 kPa (5 lbf/in.^{2}). Off river estuaries and near barrier islands there may be sand or gravel, with somewhat higher strengths. The strongest material likely to be encountered beyond the shallows is overconsolidated clay or silt, with shear strength up to about 85 kPa (12 lbf/in.^{2}) in the layer where trenching might be done. For trenching purposes, the whole area beyond the shallows could be classed as "soft ground" by the usual standards of dry land excavation, although the overconsolidated sediments are very stiff by comparison with typical subsea muds and sands.

The sea is covered by ice for 8 or 9 months of the year. Continuous freezing begins about October and is maintained until March. Deterioration and decay then set in, but coastal open water is not extensive until June. Open-water operations are effectively limited to July, August and September.

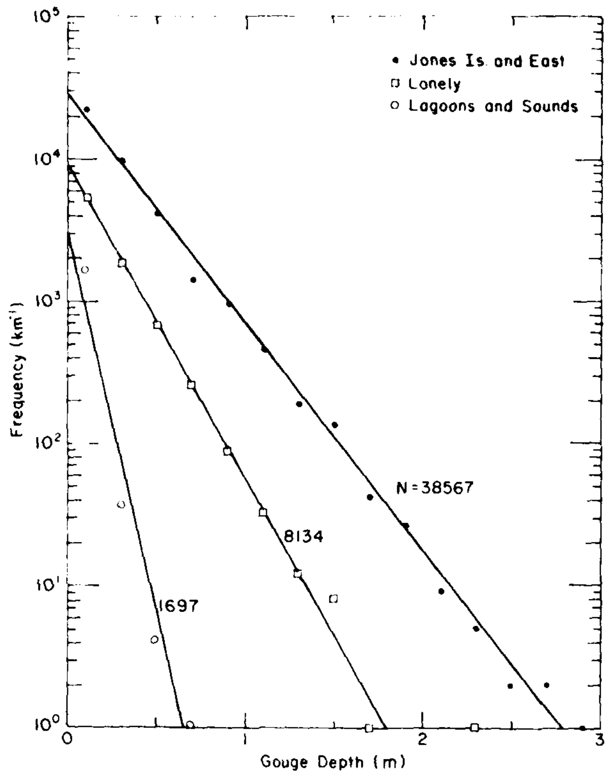


Figure 1. Gouge frequency (number of gouges per kilometre of transect) as a function of gouge depth. The data define inverse linear relations between log frequency and depth. (From Weeks et al. 1981.)

In winter, pressure ridges and shear ridges form in the sea ice, and the keels of these ridges can extend to a depth of almost 50 m (say 150 ft). Ice thrusts against the shoreline, and piles of ice debris can be pushed 50 to 100 m (160 to 330 ft) inland from the water's edge, bulldozing the beach sediments.

Movement of sea ice under the influence of wind and current causes the keels of pressure ridges to plow the seabed, forming parallel furrows, or gouges. Close to land, gouges are more or less parallel to the trend of the coastline, reflecting the ice drift. Typical furrows seem to be broad in proportion to the depth ($w/d \sim 10$), and they have raised berms along their edges. Maximum reported depths (bottom of furrow to top of berm) are 4.5 m (15 ft) in the Chukchi Sea and 8 m (26 ft) in the Beaufort. Maximum gouge depths appear to increase as water depth increases up to about 45-m (150-ft) water depth. The concentration of gouges is measured by the number of furrows per unit distance on a line drawn at right angles to the trend of the gouge system. This is the reciprocal of the mean spacing. Within a unit distance on a transect, there is a spectrum of gouge depths, and Weeks et al. (1981) have found a simple relation between the gouge depth and the number of gouges of that depth (Fig. 1). This is a simple exponential decay function which shows that, in any given place, there are lots of little gouges but only a few big ones.

The effect of water depth on gouge characteristics is not fully established, and at first sight reports from the Chukchi and the Beaufort appear to conflict. Weeks et al. (1981), whose detailed statistics extend to a maximum water depth of about 35 m (115 ft) find the number of gouges increasing with water depth. By contrast, Toimil (1979), considering water depth from 20 to 70 m (66 to 230 ft), found the number of gouges increasing with *decrease* of water depth. It seems possible that, in principle, the latter trend could hold true for the complete range of water depths, since there can be large numbers of mini-gouges in very shallow water. However, for present purposes we are concerned with "significant" gouges that are 0.3 m (1 ft) deep or more. Taking a count of gouges in some specified size range, say 0.3 to 3.0 m (1 to 10 ft) deep, it seems likely that the number, or frequency, will increase with water depth up to some limit, and thereafter decrease again as water depth increases. A guess at the water depth for maximum gouge frequency might be about 30 m (100 ft).

There is no doubt that gouges are actively forming at present, but the time period represented by the existing arrays of gouges is not known. Until a time scale for the gouging process is established, it will be difficult to make systematic risk analyses.

THE CONTINENTAL SHELF OF NEWFOUNDLAND AND LABRADOR

The coasts of Newfoundland and Labrador are steep, rocky and indented. Coastal waters are deep, with relatively high bottom relief and widespread outcropping of bedrock. Heavy glaciation has incised deep submarine valleys, and laid down thick glacial sediments (Fig. 2) ranging from clays to boulders, with shear strength possibly reaching 0.55 to 2.4 MPa (80 to 350 lbf/in.^{2}) in consolidated drift. The edge of the continental shelf is defined by the 500-m (1640-ft) isobath, which runs 100 to 300 km (60 to 190 miles) offshore. The shelf between 52 °N and 60 °N consists of a series of flat-topped banks, about 200 m (660 ft) deep, separated by "saddles" 300 to 400 m (1000 to 1300 ft) deep. Between the banks and the coast runs a discontinuous channel.

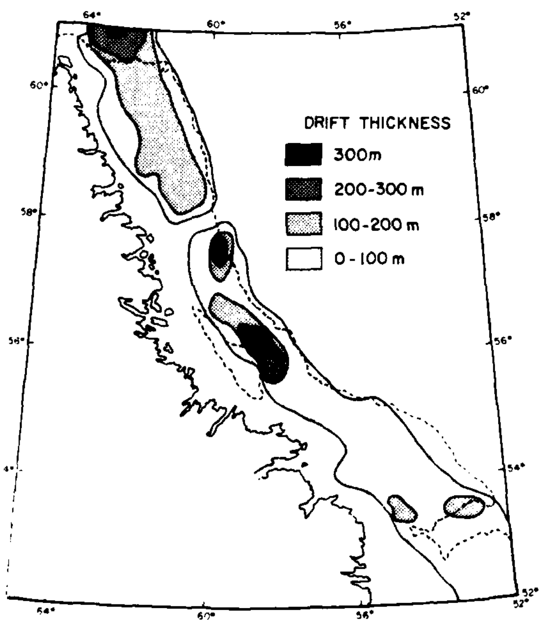
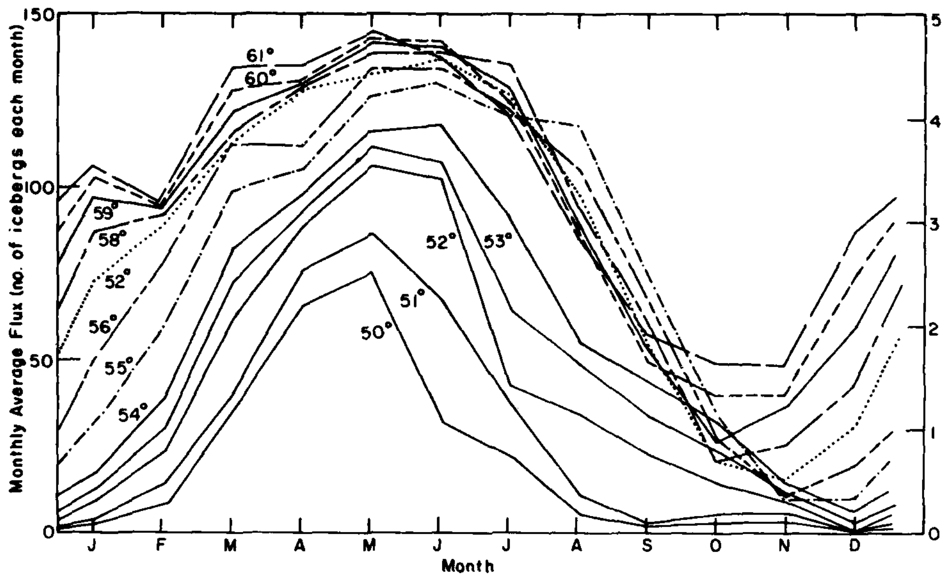


Figure 2. Thickness of glacial drift deposits on the continental shelf of Labrador. (From Gustajtis (1979); modified from data by Grant [1971], and by Van der Linden (1976).)

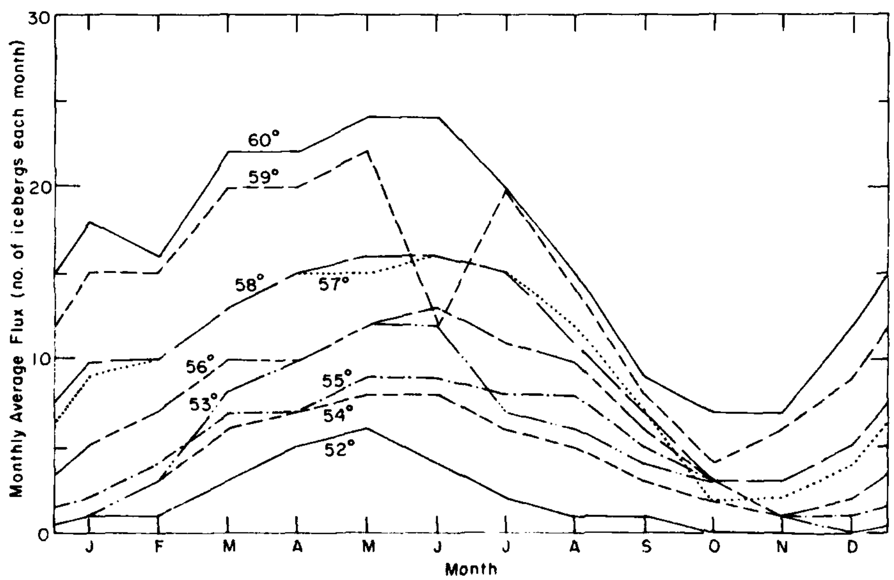
Coastal climate ranges from virtually arctic in the north (−5 °C mean annual temperature), to merely foul in the south (+5 °C mean annual temperature). Sea ice forms in sheltered inlets and bays, lasting from November to June in some places. Offshore there is no stable ice cover, but there is a southerly drift of pack ice. This reaches the Labrador coast in November, Belle Isle Strait in December, and the northern edge of the Grand Banks by late January. The sea ice begins to disappear from the Grand Banks by April, and the northern Labrador waters usually clear by July.

Sea ice presents few threats to undersea installations in this region, but icebergs are a different matter, since their deep keels can scrape and gouge the seabed to a depth of several metres. Plowing forces are developed by momentum and by water drag on the decelerating iceberg. Wherever water depth matches the draft of icebergs drifting through the area, damage to unburied pipes and cables should be expected (Table 1). Iceberg concentration reaches a maximum in early summer (May–June), and drops to a minimum in late autumn or early winter (October–December). The maximum concentration occurs at about the same time at all latitudes from 50° to 61 °N, and there is not much systematic variation in the time of minimum concentration (Fig. 3). The concentration of icebergs varies greatly from year to year; e.g., Table 2 shows an average of 263 passing the 50th parallel each year during the period 1963–67, whereas 1600 drifted south of the 48th parallel in 1972 (Gustajtis 1979). The number of icebergs passing through the Hibernia area was 1400 in 1974, 1200 in 1978, 400 in 1979, and none in 1980.

The size of icebergs in the Labrador Sea varies considerably (Table 3), and shapes vary greatly, giving variations in the draft/height ratio. This ratio varies from less than 2 to almost 10, with typical values of perhaps 3 (± 0.5). The maximum draft of present-day icebergs in this area is thought to be about 200 m (660 ft), but gouges exist in water up to 300 m (1000 ft) deep, and damage attributed to icebergs has been reported at depths of 366 and 450 m (1200 and 1500 ft).



a. Icebergs of all sizes.



b. Icebergs higher than 50 m above water level (plots of data in Table 2).

Figure 3. Monthly average flux of icebergs at various latitudes in the Labrador Sea.

Table 1. Breaks in submarine cables that are believed to have been caused by the grounding of icebergs. (Data compiled by Law and reported by Gustajtis 1979.)

Cable name	*Date*	*Water depth (metres)*	*N. Lat.*	*W. Long.*	*General location*
ICECAN cables	1963	86	59°58′57″	44°42′01″	
	1963	106	59°56′15″	44°42′46″	
	1963	146	59°04′12″	45°13′30″	
	1963	77	59°57′08″	44°41′42″	
	1963	139	59°39′31″	44°51′08″	
	23 May 64	159	59°37′42″	44°27′37″	
	21 Feb 65	209	59°56′26″	44°31′20″	
	2 Apr 65	168	59°35′30″	44°23′30″	
	3 Dec 66	154	59°35′50″	44°23′20″	
	16 June 68	156	59°34′02″	44°19′30″	Off Cape Farewell
	28 June 68	156	59°37′00″	44°21′42″	
	12 Aug 68	154	59°37′30″	44°24′18″	
	5 May 69	165	59°39′09″	44°27′30″	
	12 Sept 69	157	59°38′48″	44°29′06″	
	20 Oct 69	154	59°38′30″	44°27′45″	
	20 Oct 69	150	59°38′20″	44°29′50″	
	20 Oct 69	150	59°38′00″	44°30′00″	
	20 Feb 70	150	59°36′30″	44°30′00″	
	16 June 70	150	59°37′40″	44°30′00″	
BMEWS	3 Oct 60	366	66°24′00″	60°50′00″	Off Cape Dyer
	29 Oct 65	190	75°19′06″	69°59′40″	
	7 Sept 68	201	76°11′55″	69°59′18″	Off Cape Atholl/ Cape York
	6 Oct 68	212	76°12′04″	69°56′42″	
	12 Nov 70	185	76°19′40″	69°59′34″	

Table 2. Monthly average flux of icebergs across each degree of latitude in the Labrador Sea from 1963 to 1967. [Data from Anderson (1971), reprinted by Gustajtis (1979).]
The figures in parentheses give the monthly average flux of large icebergs, with height greater than 50 m (from Gustajtis 1979).

Flux across	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*June*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*Total*
61°N	106	95	134	135	145	138	122	86	60	49	49	87	1206
60°N	103(18)	95(16)	128(22)	131(22)	144(24)	142(24)	24(20)	87(15)	51(9)	40(7)	40(7)	74(12)	1159(196)
59°N	97(15)	94(15)	122(20)	130(20)	142(22)	141(12)	129(20)	90(14)	53(8)	26(4)	36(6)	59(9)	1119(173)
58°N	87(10)	92(10)	115(13)	129(15)	139(16)	140(16)	135(15)	95(11)	62(7)	21(3)	26(3)	43(5)	1084(121)
57°N	73(9)	88(10)	112(13)	128(15)	132(15)	137(16)	127(15)	99(12)	56(7)	20(2)	16(2)	31(4)	1019(119)
56°N	49(5)	77(7)	112(10)	112(10)	133(12)	134(13)	122(11)	106(10)	68(6)	28(3)	10(1)	19(2)	966(90)
55°N	31(2)	59(4)	99(7)	105(7)	126(9)	130(9)	120(8)	118(8)	75(5)	35(3)	11(1)	10(1)	909(64)
54°N	17(1)	39(3)	82(6)	98(7)	116(8)	118(8)	91(6)	81(5)	49(3)	32(2)	15(1)	6(0)	744(50)
53°N	12(1)	30(3)	73(8)	93(10)	111(12)	107(12)	64(7)	54(6)	33(4)	23(3)	11(1)	2(0)	613(67)
52°N	9(1)	23(1)	62(3)	89(5)	106(6)	102(4)	42(2)	34(1)	22(1)	14(0)	9(0)	0(0)	512(23)
51°N	4	14	40	76	86	67	37	11	2	5	5	0	347
50°N	3	8	35	66	75	32	22	5	1	2	3	0	263

Table 3. Size distribution of icebergs reported by the International Ice Patrol (1963–77) at various latitudes. (From Gustajtis 1979.)

Lat. (°N)	Growlers (< 1.5 m high, < 5 m long)	Small (5–15 m high, 15–60 m long,	Medium (15–50 m high, 60–120 m long)	Large (50–100 m high, 120–210 m long)
60	6.4	43.3	33.5	16.8
59	4.2	49.9	29.4	15.5
58	4.2	48.0	36.6	11.2
57	4.3	41.9	42.2	11.7
56	5.1	51.6	34.1	9.3
55	3.9	61.4	27.8	7.0
54	16.6	52.3	24.5	6.7
53	10.2	52.4	26.5	10.9
52	16.7	52.2	24.6	6.5

BURIAL DEPTH FOR PIPES AND CABLES

If ice gouging is a contemporary process, pipes or cables have to be set deeper than the deepest gouge for absolute protection. However, maximum gouge depth is up to 8 m (26 ft) for ice-ridge plowing and up to 10 m (33 ft) for iceberg plowing, while the current industry norm for burial depth is only 1.5 m (5 ft). Thus it is probably not economically justifiable to base burial depth on the extremes of gouge depth.

In order to make a systematic risk analysis it is necessary to have: 1) statistics on the concentration and dimensions of gouges, 2) data on the rates at which new gouges are formed. The statistics on existing gouges are available, or can be gathered, but so far the formation and obliteration time scales are not known. Nevertheless, Weeks et al. (1981) have made a preliminary assessment of the pipe burial problems using statistical parameters for the Beaufort Sea, together with some assumptions about rates of formation.

The frequency distribution for gouge depth (Fig. 1) can be taken as an exponential decay function of the form $e^{-\lambda x}$, where x is gouge depth and λ is a parameter (length^{-1}) which itself is a function of water depth. If we consider a cross section taken at right angles to the long axes of a set of parallel gouges, the number of gouges N that form in time T over a length L of the cross section is

$$N = \bar{g}\, TL$$

where $\bar{g}$ is the mean rate of gouge formation (gouges/km-yr). If we are concerned about the rate of formation for gouges deeper than some value x, the condition for formation of one "significant" gouge in time T is

$$e^{\lambda x} = \bar{g}\, TL$$

or

$$x = (1/\lambda)\ln(\bar{g}\, TL).$$

Weeks et al. illustrate their method by considering a pipe, 20 km long, running at right angles to the gouge pattern. They then calculate the depth to the top of the pipe which is necessary to reduce the statistical strike frequency to one hit in a specified number of years. For shallow water (≈ 5 m) they assume $\lambda = 9\ \text{m}^{-1}$, $\bar{g} = 4$/km-yr. Over a period $T = 20$ yr this gives 1600 gouges formed and a required burial depth x of 0.82 m. Over a period $T = 50$ yr, 4000 gouges form and the required burial depth for one strike is 0.92 m. For deeper water (≈ 25 m), they assume $\lambda = 3\ \text{m}^{-1}$, $\bar{g} = 7$/km-yr. This gives, for $T = 20$ yr, $N = 2800$ and required burial depth $x = 2.65$ m. Over a period $T = 50$ yr, $N = 7000$ and $x = 2.95$ m.

This neat analysis paves the way for rational decisions about burial depth and, as more data accumulate, refinements of the method can be expected. The data used by Weeks et al. do not extend out to water depths where the deepest gouges occur, and simple extrapolations of their results are probably not justifiable since, while λ may continue to decrease with increasing water depth, the trend of $\bar{g}$ ought to reverse for the deepest waters of the shelf. The important thing to note is that systematic analysis suggests more attainable burial depths than the 7-m depth that has been proposed in some recent discussions.

Some projects allow considerable latitude in selecting pipe or cable routes, and in these situations there is a strong incentive to select routes which offer natural protection. By choosing a route in the lee of a subsea ridge, or downcurrent from any bathymetric high, it should certainly be possible to achieve full protection with trenches of easily attainable depth.

DEGREE OF PROTECTION OFFERED BY BURIAL

Depth of burial tends to be used as a sole criterion of protection, but this idea is deceptive, as can be seen by considering a broad trench with very gentle side-slopes and no backfill. For a proper evaluation of protection it is necessary to consider the trench geometry, the properties and contours of the surrounding material, the backfill (if any), and the geometry and compliance of the things likely to cause damage.

In the case of ice gouging, trench geometry may, or may not, be an important factor, depending on how compliant the ice is. Suppose that the bed is being furrowed to a depth of 0.5 m by one or more projections on the keel of a bonded pressure ridge or an iceberg. As the "plow" breaks out into the side of an open trench, how far can it drop as the vertical reaction is removed? This depends on how much the pressure ridge or iceberg was uplifted by the gouging process, which in turn is determined by the strength of the bed sediment, the area indented by the "plow," and the waterline area of the parent ice mass. Given a suitable combination of these things, it is conceivable that an isolated projection might drop 1 m or more on emerging into a wide trench. On the other hand, there could be circumstances in which the "plow" would drop very little.

If we cannot be assured that the vertical compliance of a plowing keel will be low, a conservative design might call for trench geometry that is unfavorable to penetration. The big question is how "spikey" the projections on ice keels might be. Tests have shown that projections, or cantilevers, of brittle materials tend to break off rather easily when the projecting length is twice the base width, or more. If the ice projection is in the form of a wedge, pyramid or cone, it will probably be susceptible to early breakage if the tip angle is less than about 30°. Thus for a trench with no backfill, the width at the top should probably be no more than half the depth to the top of pipe in a conservative design. We might note in passing that this does not necessarily call for the vertical sides which some engineers have deemed necessary in rock trenching for cable protection.

ENVIRONMENTAL IMPACT

It can be taken for granted that gross pollution of the water and the seabed will be prohibited in a trenching operation, and the main question is how much the excavating or penetrating processes will disturb the environment. A trench represents much less of a permanent disturbance to the seabed than the ice gouges it protects against, so that is not of much concern. Spreading of excavated debris on the adjacent seabed should not be of much consequence, and generation of turbidity during trenching or burying is a localized disturbance of limited duration. Well-maintained seabed machines do not cause contamination, but expulsion of chemicals, such as polyethylene oxide additives in water jets, might be considered objectionable. In fact, the chief concern is probably the security of the line that goes in the trench, since rupture of a flowline would be really serious.

TRENCHING THE BEACH AND THE SHALLOWS IN THE WESTERN ARCTIC

Marine problems for a pipeline or cable begin at the transition from the land to the foreshore, which in the western Arctic usually means at the eroding backshore bluffs where the sea eats away at the tundra. Possibilities for crossing the bluffs include suspension, horizontal boring, angle drilling, and trenching, preferably in combination with local beach protection to stabilize or slow the erosion.

On sand or gravel beaches, the line ought to be buried below the maximum depth of summer thaw, which in Alaska might be 1.5 to almost 3 m. The required ditch can be made by conventional methods, preferably in summer or early fall.

In the shallows, out to the 2-m (6.6-ft) depth, grounded sea ice conducts heat between the bed and the air, and there is seasonal freezing and thawing of submerged sediments. Burial depth should be at least equal to the thaw depth at the water's edge, where the ground beneath the active layer is likely to be ice-bonded. Out near the 2-m isobath, where there may be only seasonal ice-bonding, down to 0.5 m (1.6 ft) or less, burial depth should be at least that required for protection against gouges. Throughout the shallows, conventional land trenching machines and techniques can be adapted. In the open water season, land machines can "wade" or operate from pontoons, and in winter and spring machines can work from the relatively smooth annual ice.

An alternative to trenching the beach and the shallows is direct burial in engineered backfill or concrete, but this seems unattractive in view of ice forces, frost heave, thaw settlement, frost damage to concrete, disturbance of beach processes, and so forth.

TRENCHING BEYOND THE SHALLOWS

Subsea trenching in relatively shallow water is usually done by equipment mounted on a seabed carriage or sled, which may be either towed or self-propelled. However, in the heavily gouged areas of the Beaufort and Chukchi the bottom might be too rough for effective operation of a seabed vehicle. If such is the case, consideration has to be given to the alternatives of carrying burying devices on a buoyant submersible or on a surface vessel.

In the following notes, discussion of equipment for trenching and embedment is necessarily intermingled with discussion of the vehicles used for carrying and propelling the equipment, but it should be kept in mind that any one type of trenching device can be carried and propelled in a variety of ways.

SUCTION, OR HYDRAULIC, DREDGING

In pure suction dredging, material is sucked off the bottom by a trailing draghead and delivered to a hopper or a disposal pipeline. The draghead may be fitted with scarifier teeth or water jets to loosen the material. While it is unlikely that pure suction dredges would be used for subsea trenching in the Arctic, their pumping requirements are essentially the same as those of the more appropriate cutterhead dredges. The pumps used may be centrifugal pumps or jet pumps.

The size of a hydraulic dredge is often denoted by the diameter of the discharge pipe, typically in the range 8 to 36 in. (0.2 to 0.9 m). The flow velocity needed to entrain and lift solids depends on the size and specific gravity of the particles (i.e. on fall velocity), on the pipe diameter, and on the required transport mechanism (e.g. uniform suspension, turbulent diffusion, saltation). In a vertical pipe, water velocity only has to exceed particle fall velocities, which are typically less than 1 m/s, but in a horizontal pipe velocities have to be higher in order to provide the boundary shear and turbulent exchange needed for entrainment and transport. The useful output of the dredge, usually reckoned in terms of the volume of solids pumped per unit time, depends on the flow rate and the concentration, or mean specific gravity of the mixture (typically up to 20% solids by volume). The required pump power depends on pipe diameter, flow rate, and the total head on the system (lift + line loss). For a given total head, flow rate is proportional to velocity and to the square of pipe diameter; power is proportional to the cube of velocity and the square of pipe diameter, but of course friction loss is a strong inverse function of diameter.

Figure 4 gives an idea of design and performance characteristics of existing hydraulic dredges. These usually operate in shallow water, but for sand and gravel mining some dredges work in depths over 30 m (100 ft), and even up to 70 m (230 ft).

For work in well-consolidated sediments (including gravel) and in weak rock (especially coral), suction dredges require a cutter to disaggregate the material. The dredge vessel is fitted with a pivoted boom, or "ladder,"which carries at its lower end a rotating "basket" fitted with blades and/or cutting teeth. This type of dredge is known as a "cutterhead," or "cutter-suction" (CS), dredge (Fig. 5).

The ladder of a CS dredge carries the suction line and the propeller shaft on which the cutterhead is mounted. The cutter may be powered by direct shaft drive from the surface, or by submerged hydraulic or electric motors, with power typically ranging from a few hundred horsepower to about 2000 hp. Head diameters are typically up to about 3.7 m (12 ft) with rotation speeds in the range 10 to 30 rpm (bigger heads turning at lower speeds). Ladders range in length from about 8 to over 46 m (25 to 150+ ft), and they usually operate at angles up to 45° from the horizontal. In overall size, CS dredges range from small knockdown portable machines to a 32,000-ton semisubmersible walking platform carrying a 5000-hp cutterhead.

A CS dredge suitable for trenching in the western Arctic might have about 600 hp on the cutter and about 1600 hp driving the pumps (dredge pipe 75/65 cm, or 30/25 in.). A possible mode of operation would be to draw the cutterhead along the trench line without swinging the ladder from side to side, using anchors and winches for propulsion.

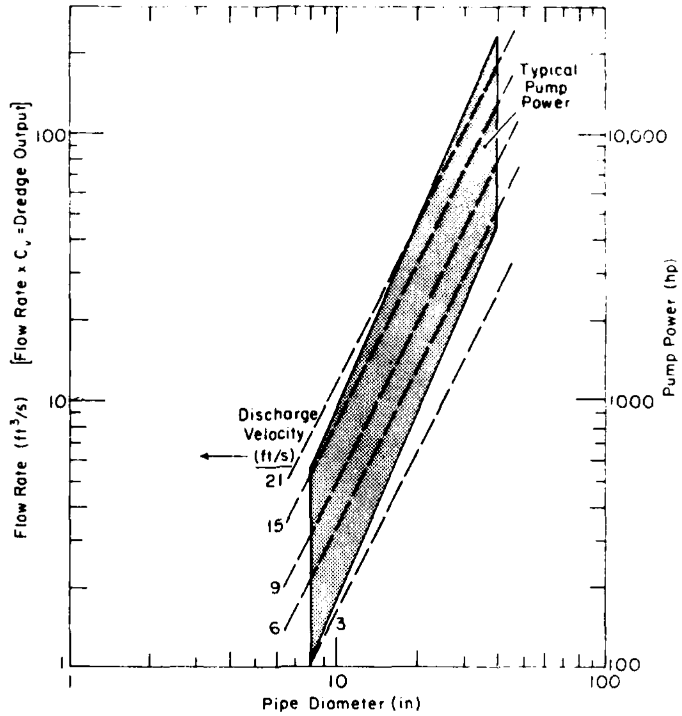


Figure 4. Representative values of flow rate and pump power for suction dredges of various sizes.

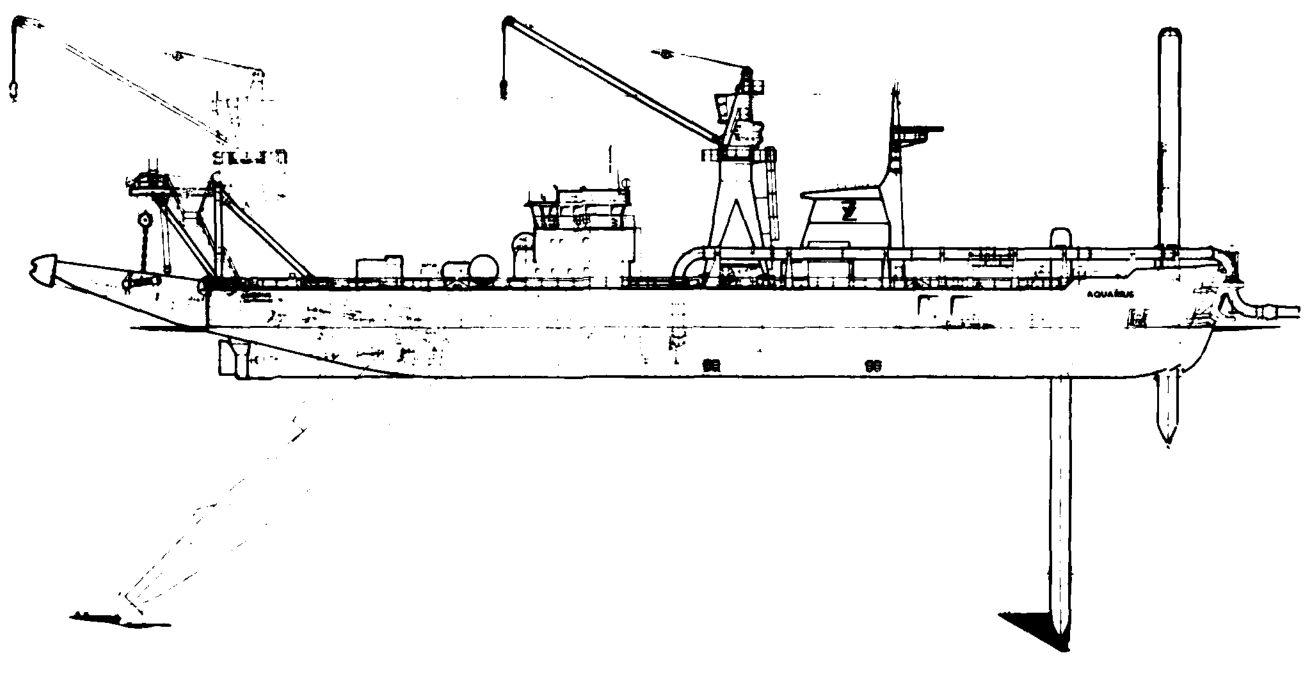


Figure 5. Ocean-going cutterhead dredge capable of working to a depth of 25 m (cutter power 2000 kW, total pump power 6700 kW, power on propellers 3600 kW).

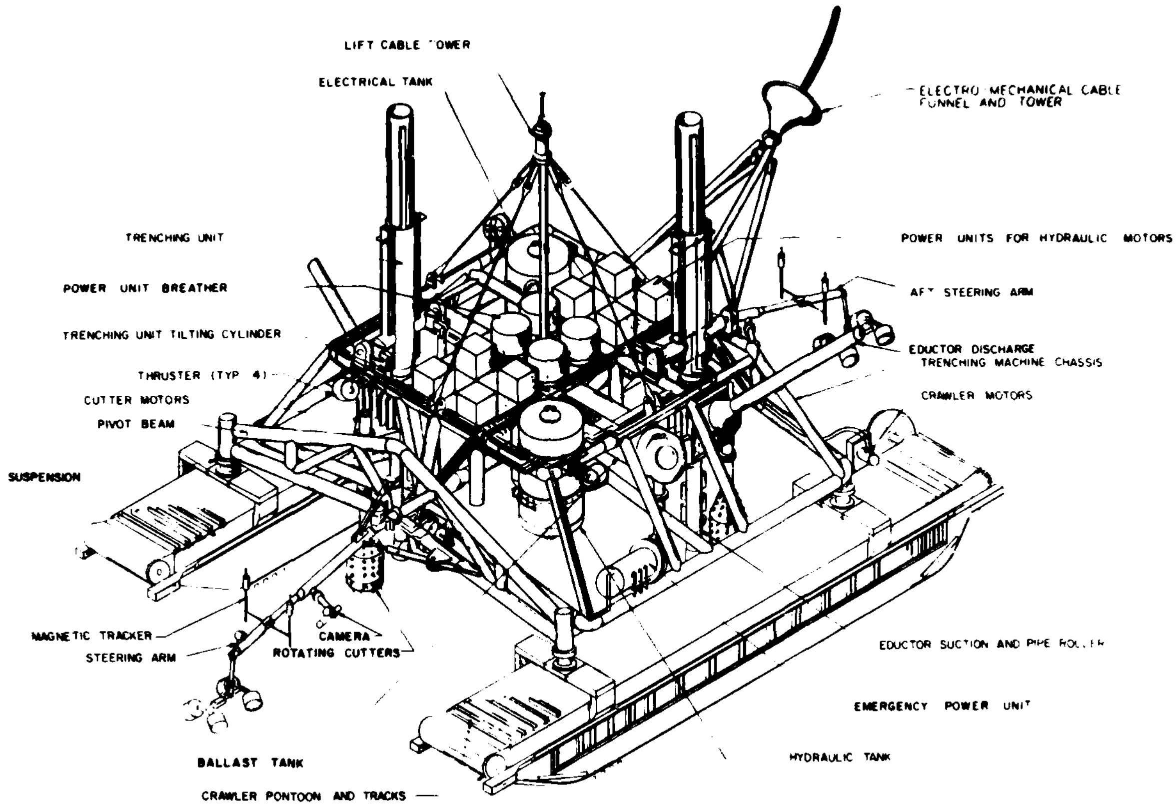


Figure 6. Bottom-traveling cutterhead machine.

BOTTOM-TRAVELING CUTTERHEAD DREDGES

To overcome the limitations of water depth and sea state for conventional dredges, bottom-traveling cutterhead dredges have been developed. These may travel independently on seabed sleds or carriages, or they may "ride" the pipe if it is big enough. The machine is propelled either by tow from the surface or by its own crawler tracks. Buoyancy is controllable in order to facilitate recovery and to adjust bed contact pressure. Dredge material may be pumped to the surface, or it may be discharged under water by either pumps or eductors. Machines built so far can be divided into two main groups and a number of subgroups.

1. Free-cutting machines (cutterheads mounted on slewing booms): a) single boom, b) twin boom.

2. Fixed-cut milling machines (one or more cutters set for a particular trench cross section): a) vertical axis cutter, b) horizontal axis cutter—axis in line of travel, c) horizontal axis cutter—axis perpendicular to line of travel, d) inclined axis cutters set to control trench sideslopes.

Arrangements for operation and control have included: 1) operation solely by divers, 2) atmospheric pressure control capsule on the machine, 3) remote control (manual or computer) from the surface. Power is almost invariably supplied from the surface through an umbilical, usually as high-voltage electric power.

So far, weight (in air) has been in the range 50 to 200 tons. Power supplied to a single cutterhead has ranged from 10 to 360 hp, while total power for all functions on a single machine has ranged up to 1500 hp. Total power utilized by a single machine, including surface pumps, has gone as high as 3500 hp. Design excavation rates have ranged up to about 10 m³/min (350 ft³/min) for loose material. Trenching speeds vary with the material and the size of the trench. Self-propelled machines typically have maximum crawl speeds in the range 6 to 9 m/min (20 to 30 ft/min), and presumably trench can be cut at these speeds under very favorable conditions. In stiff clay, rates of 0.6 to 1.1 m/min (2 to 3.5 ft/min) have been achieved under operational conditions, although at least one manufacturer has forecast a rate that is an order of magnitude higher.

Companies who have designed or built underwater cutterhead machines include Saipem, Sub Sea Oil Services, Groupement EPM, Tecnomare, Brown and Root, Sumitomo, Kvaerner-Myren, and Oceanonics.

PLOWS

Conventional moldboard plows, with or without coulter blades, have been used successfully for burying both cables and pipelines in relatively weak submarine sediments. Bell Laboratories has been developing its "Sea Plow" machines since 1966 for deep ocean cable burial in water to 900 m (3000 ft) deep. The sled-mounted Sea Plow IV weighs close to 25 tons and cuts a furrow 0.4 m (16 in.) wide by 0.61 m (24 in.) deep, with towing forces of the order of 25 tons or more. Pipeline plows have been produced in recent years for work in such places as the North Sea, the Bass Strait, and the Canadian eastern Arctic, with much of the development spearheaded by R.J. Brown and Associates (Fig. 7). Typical modern pipeline plows (as represented by the developments of R.J. Brown, Smit International and Panarctic Oils) are big and heavy machines (15-25 m long, 30-70 tons in air) capable of ditching to about 1.5 m depth. Carried on either sleds or rollers, they can dig shallow (1.2 m) trench at up to 3 km/hr (1.9 mph) in soft material.

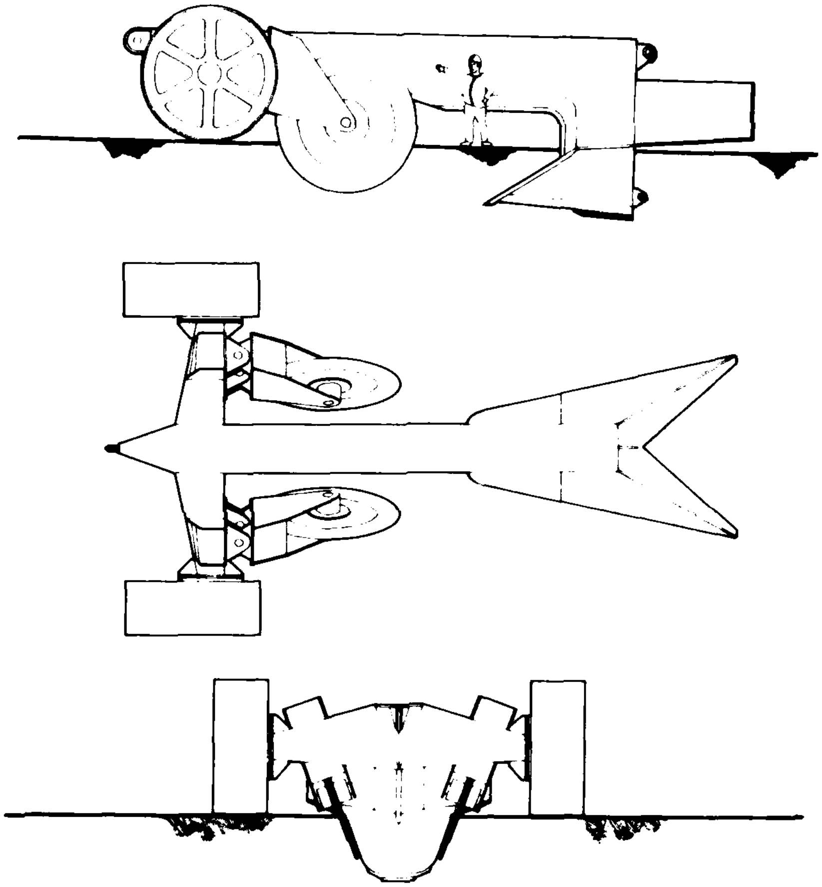
Plowing forces are determined by the soil properties, the dimensions of the furrow, the design characteristics of the tool and, to a small extent, by the plowing speed. Procedures for calculating the plowing force are available, but for present purposes a simple index is more useful. Palmer et al. (1979) characterize dynamic similitude for geometrically similar plows by the dimensionless group (D/cH^2), where D is the mean "draft" (plowing force, or drawbar pull), H is the mean depth of furrow, and c is the undrained shear strength of the soil (measured 1 m below the seabed for full-scale plows). A full-scale plow tested in soils with c ranging from 4 to 9 kPa gave values of (D/cH^2) from 8 to 33, and the same plow operated at Drake Point, Melville Island, gave (D/cH^2) = 9.8 with c = 3 kPa. From figures that have been quoted for the Bell Sea Plow, one might guess corresponding values of (D/cH^2) closer to 30.

The relatively strong sediments of the Beaufort Sea ($c \approx 20$ to 85 kPa) could be plowed, as we see from the plowing done by ice keels, but plowing forces might be excessive. Taking (D/cH^2) = 10, c = 40 kPa, and H = 1.5 m, D = 0.9 MN (101 tons). Increasing H to 2.5 m increases the required pull to 2.5 MN (281 tons). If provision has to be made for working in soils at the upper end of the strength scale, say c = 80 kPa, then the forces have to be doubled. These forces (100-600 tons) are very high—above the typical range for deck machinery on ships, and even above the maximum capability of ordinary commercial traction winches (< 300 tons). The outlook becomes even more pessimistic if (D/cH^2) turns out to be greater than 10.

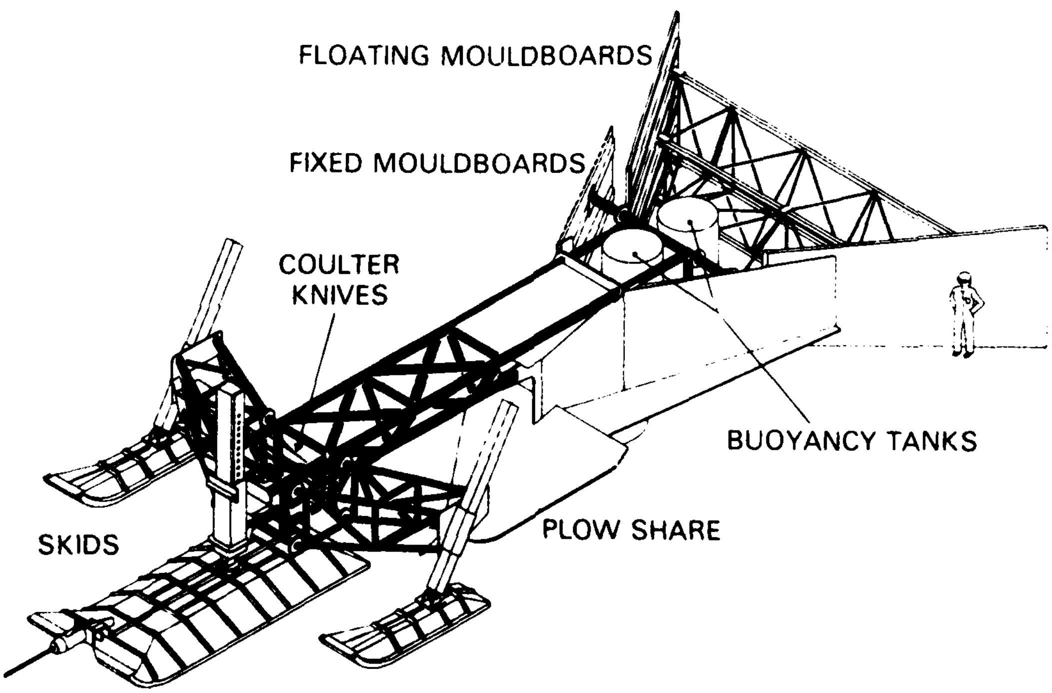
Deep-ocean plows are pulled continuously by cable from a ship or tug. The thrust available from screw propulsion is quite limited—in the range 7 to 16 kgf/hp, or 15 to 35 lbf/hp (Mellor 1980a). The maximum bollard pull of the world's biggest tugs is less than 200 tons, while the largest icebreakers might give about 400 tons at 1 knot. In relatively shallow water it is clearly more economical to winch from an anchored vessel if high towing forces are required. The arithmetic for cables, winches and anchors is given elsewhere (Mellor 1979). Another option for relatively shallow water is to pull the plow with a rigid towbar attached to a surface vessel, which itself is kedged against anchors. This arrangement is described in at least two patents, and it was used to plow-in a 0.25-m (10-in.) gas pipeline under Turnagain Arm, Anchorage. The plow was mounted at the end of a 100-m (330-ft) boom, which itself was attached to a lay barge through a trunnion. The barge was winched forward to multiple anchors set by a tug, with additional side anchors to stabilize against tidal currents of up to 7.6 knots. The design plowing depth was 1.5 m (5 ft), but only 0.6 m (2 ft) was possible where current scours exposed the strong gravel layers.

Another way to pull a plow is by mounting it on a self-propelled seabed vehicle. This has been done, e.g. by Comex, but the pulling force is limited by the submerged weight of the vehicle. About the best that can be expected for the drawbar coefficient (drawbar pull/vehicle weight) is 0.8, so that the Comex machine (16 tonnes submerged) might give up to 13 tonnes of pull. The maximum submerged weight for existing subsea crawlers is about 80 tonnes, so the maximum attainable drawbar pull is around 60 tonnes. On soft bed materials it would be more realistic to assume a drawbar coefficient of about 0.3.

Many underwater plows are fitted with low pressure water jets to improve their performance (Fig. 8). The function of the water jets is stated variously as: "flushing," "lubricating," "fluidizing," "scouring," or "jet blasting." The general



a. The R.J. Brown 50-ton plow for cutting a ditch 1.2 m deep in the North Sea.



b. A 29-ton plow designed by R.J. Brown for Panarctic Oil.

Figure 7. Moldboard plows.

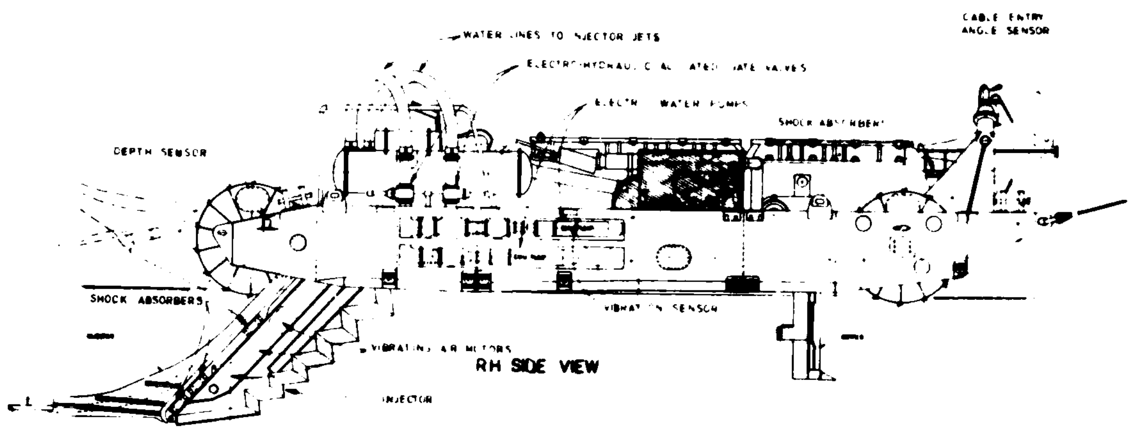


Figure 8. The Harmstorf "Vibro-Hydrojet" cable embedment unit.

subject of water jetting is discussed separately later.

Some plows incorporate devices for oscillating or vibrating the moldboards or blades (Fig. 8), the intention being to improve cutting capabilities or to fluidize the soil. Vibratory and percussive devices will be discussed separately.

RIPPERS

On dry land, rippers often take over when the ground is too hard for plows. In tough soils and "rippable rock" the typical equipment is a single-shank ripper on a large crawler tractor (> 20 tons weight). For ripping to a depth of 1.5 m (5 ft) or more in hard ground, the required horizontal force could be in the range 25 to 50 tons, with a vertical force of the order of 15 tons when starting a run.

General purpose underwater construction tractors have been built and tested by Komatsu and Hitachi but, as far as is known, they have not yet been used for major projects. The Komatsu has an operating weight of 31 tonnes submerged, which could give up to 23 tonnes of drawbar pull on favorable materials (the track pressure is 74 kPa or 10.7 lbf/in.^{2} submerged, which is rather high for operation on soft material). The installed power is 125 kW (168 hp), so that at a forward speed of 0.51 m/s (1 knot) the power limits the possible drawbar pull to about 23 tonnes.

For underwater application of rippers it might be best to mount one or more tools on a towed sled or carriage (e.g. R.J. Brown or Harmstorf), or else on one of the very large subsea crawlers that have been developed in recent years (e.g. Brown and Root MUT, Land and Marine TM IV, Heerema Eager Beaver).

Another possibility is to attach one or more rippers to the suction head of a hydraulic dredge. With a large vessel of 12,000 hp, the available pull would be about 120 tonnes (130 tons), assuming a propulsion coefficient of 10 kgf/hp (22 lbf/hp).

WATER JETS

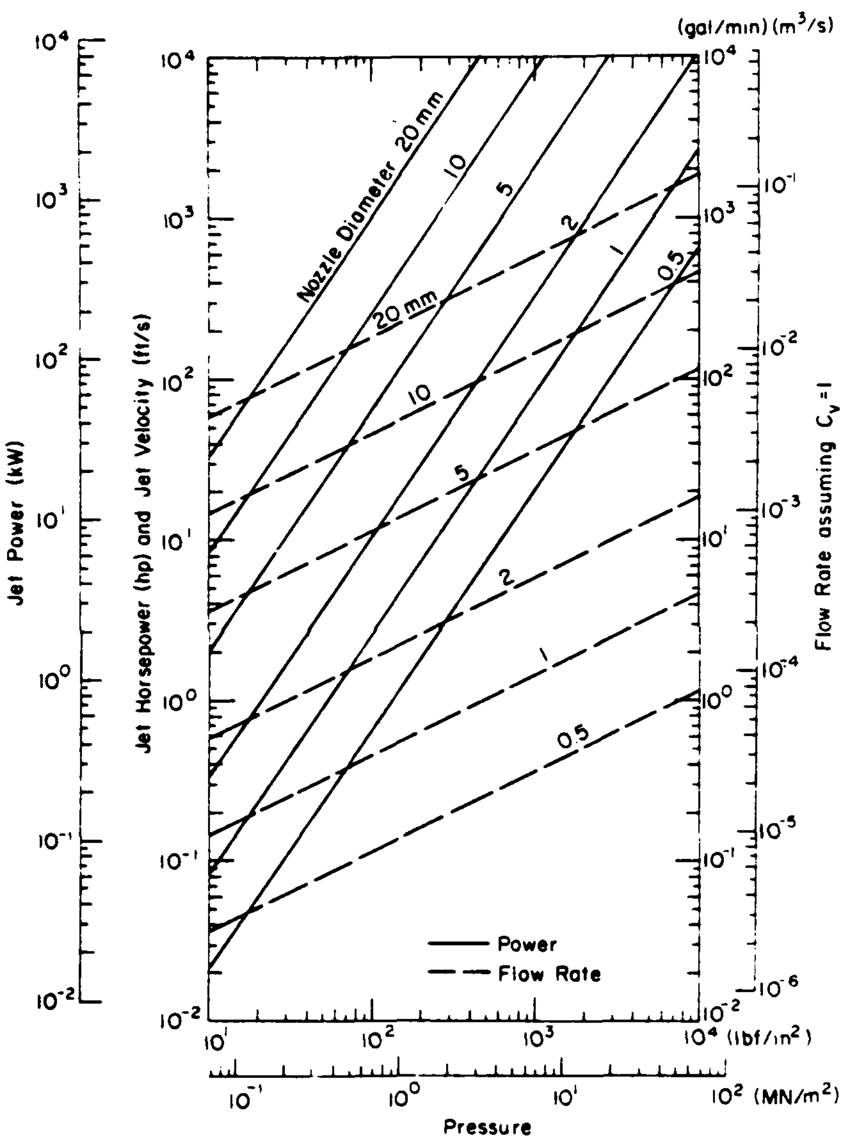
Water jets can range from low pressure devices, intended primarily for flushing and lubricating, up to very high pressure systems capable of penetrating hard rocks.

Low-pressure fluidization of loose sediments can be used to bury pipes and cables without gross displacement of the soil. Jets operating at nozzle pressures as low as 138 kPa (20 lbf/in.^{2}) can "fluff-up" the soil, increasing pore pressure, separating and agitating the particles, and destroying the shear rigidity of the material. Low pressure water jets are sometimes used alongside compressed air jets.

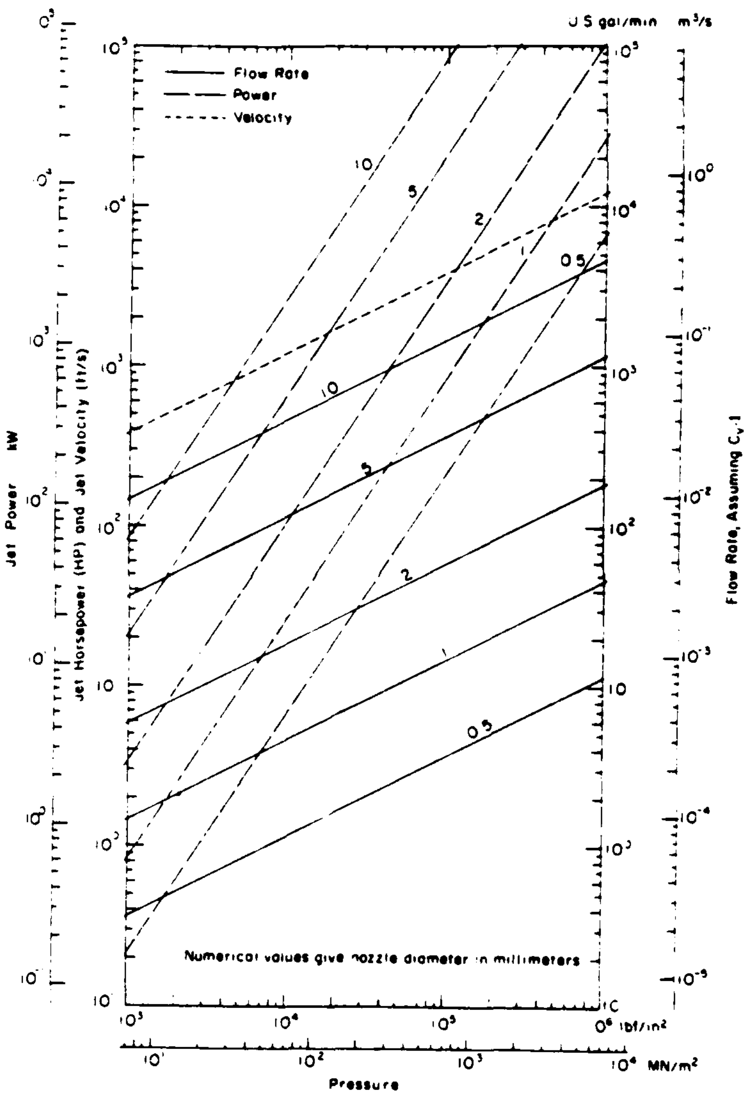
Jets working at higher nozzle pressures, up to 20 MPa (3000 lbf/in.^{2}) for some equipment, are capable of penetrating cohesive soils, and they can displace material by creating strong local currents.

At low nozzle pressures the power demands for jets are modest, so that relatively large individual nozzles can be used, and multiple nozzles are feasible. However, power is proportional to the square of nozzle diameter and to nozzle pressure raised to the power $^3/_2$, so that power demands rise rapidly as pressure increases, and it becomes necessary to use small nozzles, and relatively few of them. A general impression of the relationship between power, jet velocity, flow rate, nozzle size, and pressure is given by Figure 9.

High-pressure water jets are capable of pene-



a. Low-pressure jets.



b. High-pressure jets.

Figure 9. Hydraulic power and flow rate as functions of nozzle pressure and nozzle diameter for water jets.

trating hard materials, up to and including granite. A lower limit for "high pressure" can be taken as 69 MPa (10,000 lbf/in.^{2}), while the practical upper limit for continuous jets is perhaps around 690 MPa (100,000 lbf/in.^{2}). The initial impact of a water drop or an intermittent jet against a solid surface gives a peak contact stress of approximately $\rho c v$, while the sustained pressure imposed by a continuous jet is $\rho v^2/2$, where ρ is water density, v is impact velocity, and c is the sonic wave velocity. Thus there is a tendency to strive for high jet velocity, which increases with the square root of nozzle pressure. However, practical constraints necessitate a decrease of nozzle diameter, and hence jet length, for very high-pressure systems. This means that, with high-pressure equipment, nozzle standoff has to be small, penetration is very limited, and the area of attack is small. One possibility for reaching very high pressures and velocities, at least in air, is to fire intermittent slugs of water instead of a continuous jet. Other possibilities for cutting hard materials include the use of cavitating jets or jets into which solid particles are introduced.

For now, high-pressure jet cutting which involves continuous jets, pulsed jets, or cavitating nozzles probably has to be regarded as exotic technology for subsea trenching. Low-pressure jetting is well established as a practical method for burying subsea pipes and cables. It has strong practical merits, although in energetic terms it is probably not a very efficient method. Rockwell (1975) found that, for actual jetting operations, specific energy was in the range 90 to 2700 lbf/in.^{2} (0.4 to 12 hp per ft^3/min of excavation rate).

SUBSEA DISC SAWS AND WHEEL DITCHERS

On land, bucket-wheel ditchers can be used for trenching in most soils, in weak rocks, and in some types of frozen soils. Typical machines rotate to give an upcut milling action, with peripheral tool speeds ($\pi \times$ diameter $\times$ RPM) in the range 1 to 3 m/s (200 to 600 ft/min). Power/weight ratios are in the range 0.003 to 0.005 hp/lbf. Nominal power density (usable rotor power divided by one-quarter of the swept perimeter area) is in the range 24 to 80 kW/m^2 (3 to 10 hp/ft^2). For land trenching in moderately strong rocks, concrete, and high-strength frozen soils, wheel ditchers give way to disc saws, which are generally much narrower and of somewhat smaller diameter. Disc saws are also upcut machines, and peripheral tool speeds are in the range 1 to 5 m/s (200 to 1000 ft/min). Power/weight ratios are in the range 0.005 to 0.01 hp/lbf. Nominal power densities are about 3000 kW/m^2 (30 to 40 hp/ft^2) for North American machines, and about 20 to 60 kW/m^2 (2.5 to 8 hp/ft^2) for Soviet machines designed to cut frozen ground.

Disc and drum cutters are being developed for underwater use. Some years ago the U.S. Navy Civil Engineering Laboratory experimented with a modified Vermeer T-600 rock saw, and a Florida company has been operating a sled-mounted narrow trenching wheel (8 in.) in coral, cutting to depths of 1.7 m (5.5 ft). Comex has developed and operated a relatively small seabed crawler (Fig. 10) which carries a 2.3-m- (7.5-ft-) diameter wheel (Auberty et al. 1980). In hard North Sea clay the machine trenched to a depth of 1.2 m (4 ft) at an average rate of 2 m/min (6.6 ft/min), with a best speed of 3 m/min (9.8 ft/min). The wheel is said to cut soft rock (3500 lbf/in.^{2} compressive) at 0.6 m/min (2 ft/min) with a 1-m (3.3-ft) trench depth. This machine is unusual in that it is controlled by a diver riding (exposed) on the machine. Operators are transported in a bell, and saturation diving is employed for deep work (the North Sea job was at 140 m, or 460 ft).

A very big disc, or drum, machine has been developed by Land and Marine Engineering Ltd. The cutter of this subsea crawler is a horizontal-axis drum, 4.5 m (14.8 ft) in diameter and 0.6 m (2 ft) wide. It is driven by two 200-kW (268-hp) electric motors through reduction gearboxes at 10 to 15 rpm, giving peripheral tool speeds in the range 140 to 210 m/min (460 to 700 ft/min). Since it is designed for rock-cutting (initially for trenching in chalk under the English Channel), the drum is fitted with carbide-tipped mining machine picks. The picks are scrubbed by water jets supplied from two 450-hp motor/pump units at a rate of 52,000 litres/min (13,700 gal/min, or about 1 ton/s). The normal range of trenching depth is 0 to 1.5 m (0 to 4.9 ft), with maximum penetration of 1.65 m (5.4 ft). On the basis of land tests and sea trials the predicted trenching speeds are: up to 4 m/min in sand and silt, up to 2.5 m/min in soft rock, and up to 1 m/min in hard rock. An interesting point is that the designers expect to be able to operate a modified cutter in rock that would be considered too strong for economical machine trenching on land. The nominal power density, as defined above, is 190 kW/m^2 (23 hp/ft^2), which is higher than values for dry-land wheel ditchers, but lower than values for North American rock saws. The hydrodynamic resistance on the underwater

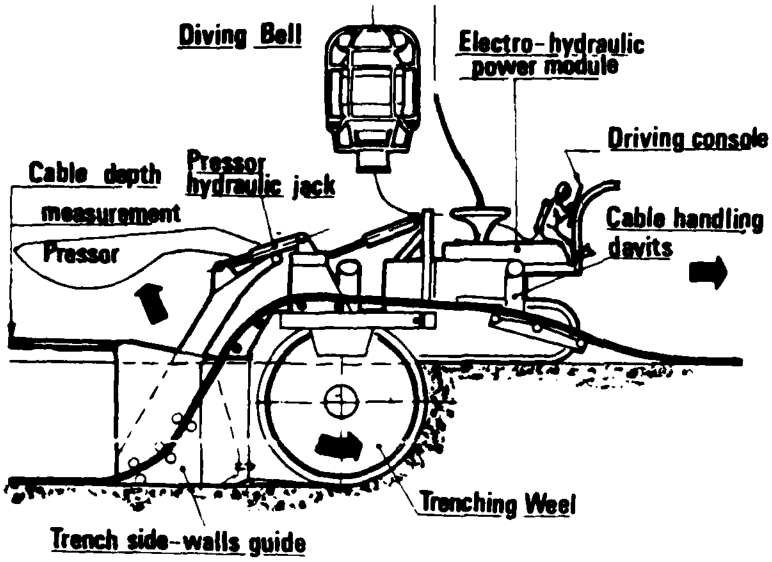


Figure 10. Comex seabed trencher. (From Auberty et al. 1980.)

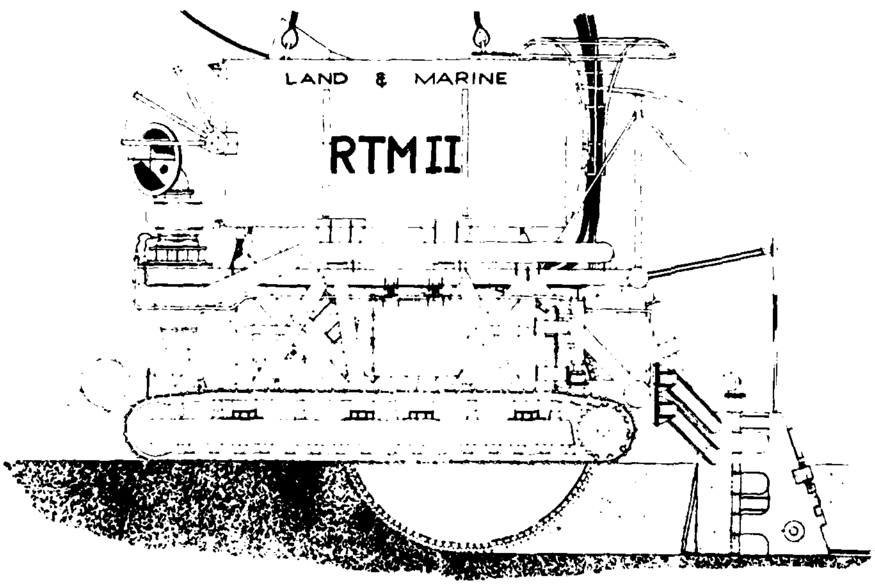


Figure 11. The Land and Marine RTM II seabed rock trencher.

drum is appreciable, at an estimated value of 80 kW (107 hp). However, the L&M machine, designated RTM II, is only intended to bury its drum to a maximum of 37% of the diameter (wheel ditchers and some saws can exceed 50%). The whole machine weighs 120 tonnes in air, with submerged weight variable between 15 and 80 tonnes. Maximum design value for tractive thrust is 55 tonnes (61 tons), and there is a kedging winch capable of providing another 45 tonnes of pull. The two tracks, each driven by a 50-hp variable-frequency electric motor, give speeds up to 7.5 m/min (25 ft/min). Overall dimensions of the machine are: 13 m (42.6 ft) long, 6.5 m (21.3 ft) wide, 7.32 m (24 ft) high. The range of operating depth is 3.5 to 100 m (11.5 to 330 ft).

A 50-ton crawler disc machine has also been developed by Coflexip, but full details are not yet available. The saw cuts a trench 0.4 m wide and up to 1.2 m deep.

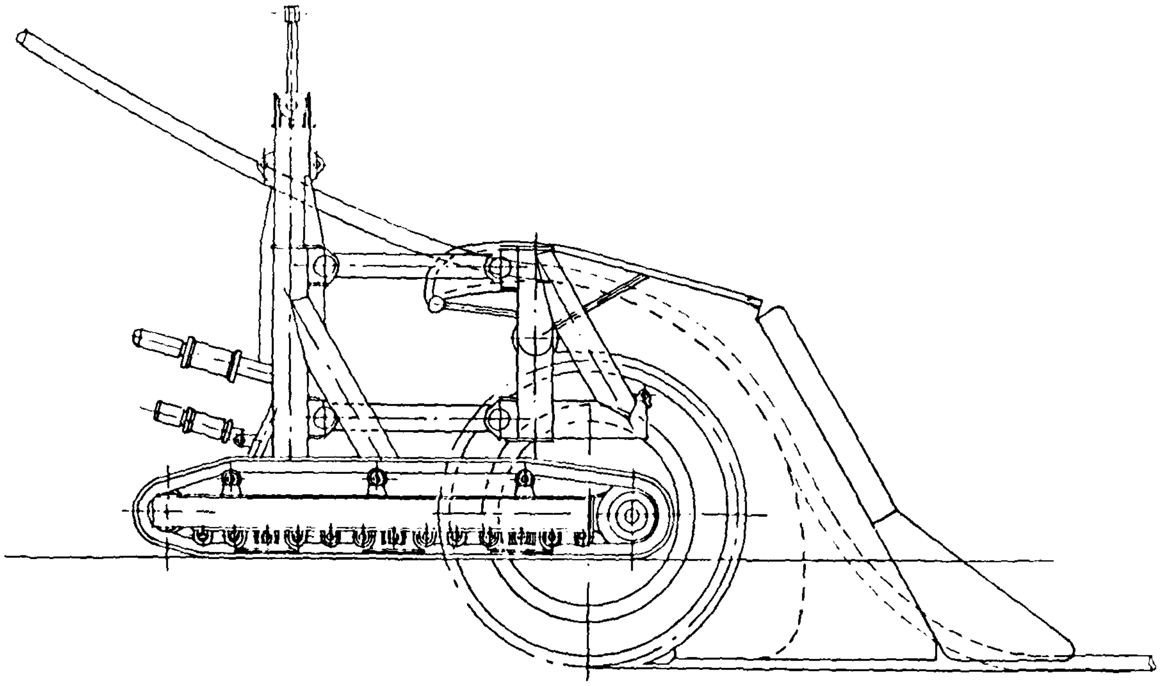


Figure 12. The Coflexip machine with the cutter disc and the share in the working position.

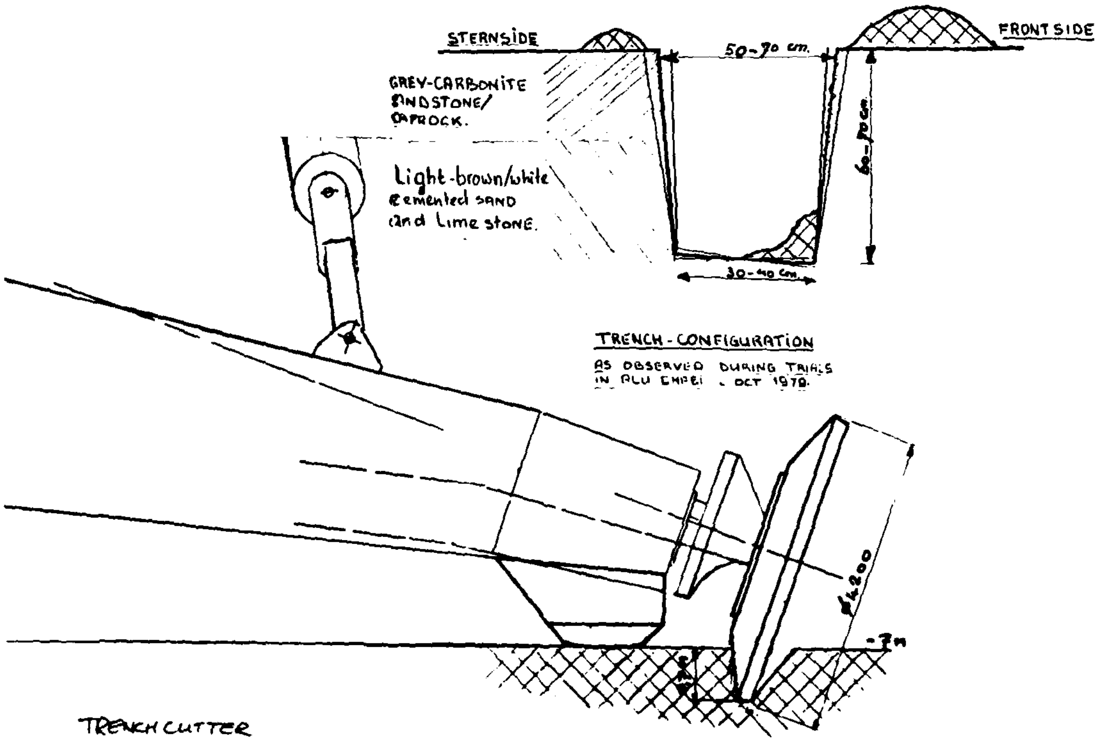


Figure 13. A beveled disc cutter substituted for the cutterhead of a conventional CS dredge (Volker Stevin Dredging).

Subsea disc saws can be supported and driven from a surface vessel if the water is not too deep. Volker Stevin Dredging modified a cutter-suction dredge, the Sliedricht 30, for trenching experiments in hard bottom materials (20 MPa, or 3000 lbf/in.^{2}) at Abu Dhabi. The basket of the cutterhead was replaced by a beveled wheel (4.4 m diam) that itself was fitted with conventional "bullet bits," as used on mining machines (Fig. 13). The dredge was traversed sideways by winches, cables and anchors, while the ladder was held relative to the hull at zero swing angle. The wheel, which could rotate at 0 to 30 rpm, gave best results at 10 to 20 rpm, with corresponding linear tool speeds of 2.3 to 4.5 m/s (450 to 900 ft/min). Trenching rate varied with trench depth and properties of the bottom material in the range 3 to 8 m/min (10 to 26 ft/min), or equivalent to 0.18 to 0.48 km/hr. Power on the cutter was 500 to 600 hp.

Twin-disc machines have been considered for rock trenching, the idea being to saw parallel narrow kerfs at the edges of the trench, and then break out the uncut block, which may have the proportions of a cantilever slab.

SUBSEA LADDER TRENCHERS AND CHAIN SAWS

The ladder trenchers used on land for digging in soils range from very small devices to large crawler-mounted bucket-chain machines. Their digging chains run at speeds in the range 0.5 to 5 m/s (100 to 1000 ft/min), with the biggest machines having bucket speeds of 0.5 to 1.3 m/s (100 to 250 ft/min). Forward traverse speeds of the machines are in the range 0.06 to 9 m/min (0.2 to 30 ft/min), and ratio of forward traverse speed to chain speed (i.e. tool speed) is in the range 10^{-1} to 10^{-4}. Power/weight ratios range from 0.003 to 0.01 hp/lbf, with the biggest machines having the lowest values. Nominal power density, defined as the cutting power divided by the rated cutting cross section (depth × width of trench), is in the range 40 to 160 kW/m^2 (5 to 20 hp/ft^2) for typical soil trenchers, and in the range 8 to 40 kW/m^2 (1 to 5 hp/ft^2) for big bucket-chain machines. For trenching in rock on land, the typical ditcher ladder, with its loosely supported chain, is replaced by a more rigid saw like a scaled-up wood-cutting chain saw. The typical hardfaced blades or teeth of the soil trencher are replaced by carbide-tipped mining tools. Coal saw cutter bars are readily adaptable for trenching in weak rocks, and they have been used widely for cutting frozen ground in the U.S.S.R. In order to trench in moderately strong rocks and high-strength frozen soils, bigger and more robust saws are needed. A good example is the BorTunCo Roc-Saw. The chains on coal saws and rock saws typically run at 2 to 4 m/s (400 to 800 ft/min), while the saws traverse through the work at about 0.3 to 3 m/s (1 to 10 ft/min). The ratio of traverse speed to tool speed is in the range 10^{-3} to 3×10^{-2}. Power/weight ratios for ditching saws and coal cutters are about 0.007 to 0.013 kW/kgf (0.004 to 0.008 hp/lbf). Power densities, as defined above, are 160 to 400 kW/m^2 (20 to 50 hp/ft^2). Ladder trenchers and chain saws are well adapted for deep cutting. Although most trenching is limited to 1.8 to 2.4 m (6 to 8 ft) depth, both soil trenchers and rock saws have cut to depths exceeding 7 m (23 ft) on land.

Ladder trenchers are now being used for subsea trenching in both soft sediments and weak rocks.

The Tecnomare TM-402 (Fig. 14) is a relatively small subsea crawler fitted with a ladder trencher which digs trenches 0.25 to 0.4 (0.82 to 1.3 ft) wide up to a depth of 1.5 m (4.9 ft). In sand and clay it can work up to the maximum crawl speed of 400 m/hr (22 ft/min), and tests on concrete have given rates of 10 to 20 m/hr (0.55 to 1.1 ft/min). The maximum chain speed is 2.7 m/s (520 ft/min), and the power available to the cutter is about 110 hp. The weight of the machine is 21.6 tonnes (24 tons) in air, and normal submerged operating weight is 13 tonnes (14 tons). Track pressure is 2 tonnes/m^2 (2.8 lbf/in.^{2}) on the seabed, and 2.5 tonnes/m^2 (3.6 lbf/in.^{2}) under maximum working loads. Without the cable guide, the machine is 5.6 m (18.4 ft) in length and width, and its height is 4 m (13 ft). Maximum operating depth is 160 m (525 ft). The umbilical supplies electricity to a 200-hp motor, which drives hydraulic pumps to power the hydraulic motors on the cutter and the tracks. A separate hydraulic umbilical allows divers to perform setup and initial maneuvering with the electric power switched off.

Chambon has built a somewhat heavier subsea crawler (Fig. 15) with a ladder that is designed to cut a trench 0.6 m (2 ft) wide up to 1.7 m (5.6 ft) deep in the chalk under the English Channel (250 bars, or 3600 lbf/in.^{2}, compressive). The chain is driven by two hydraulic motors with a total power of 120 kW (161 hp). The umbilical supplies the machine with 165 kW of electrical power. During sea trials the machine dug trench and laid cable to a depth of 1.2 to 1.5 m (4 to 5 ft) at rates of 65 to 100 m/hr (210 to 330 ft/hr) at four sites. In another trial, rates averaged 90 to 120 m/hr (295 to 390 ft/hr) with depths of 1.3 to 1.7 m (4.3 to 5.6

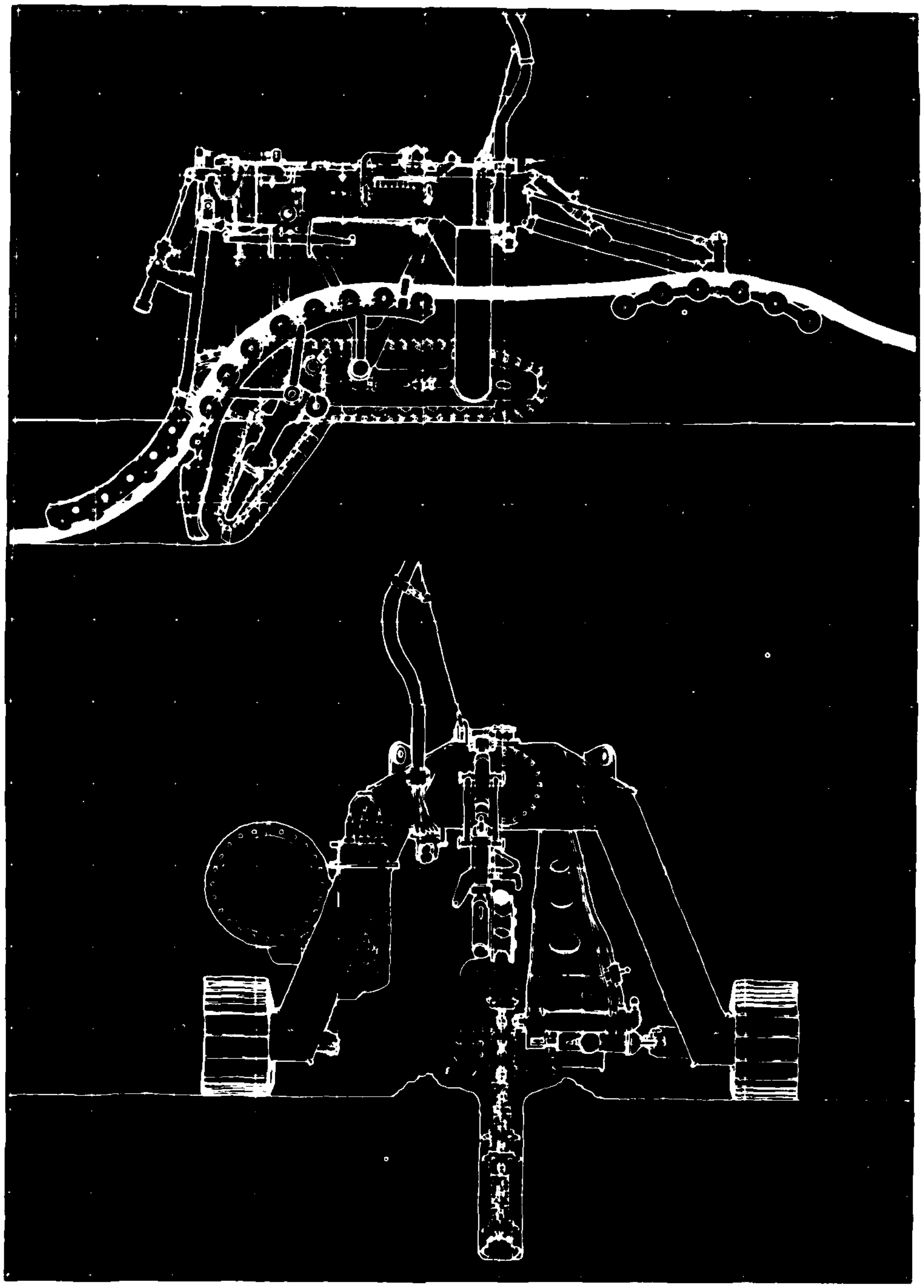


Figure 14. The Tecnomare TM 402 trencher for cables and small pipes.

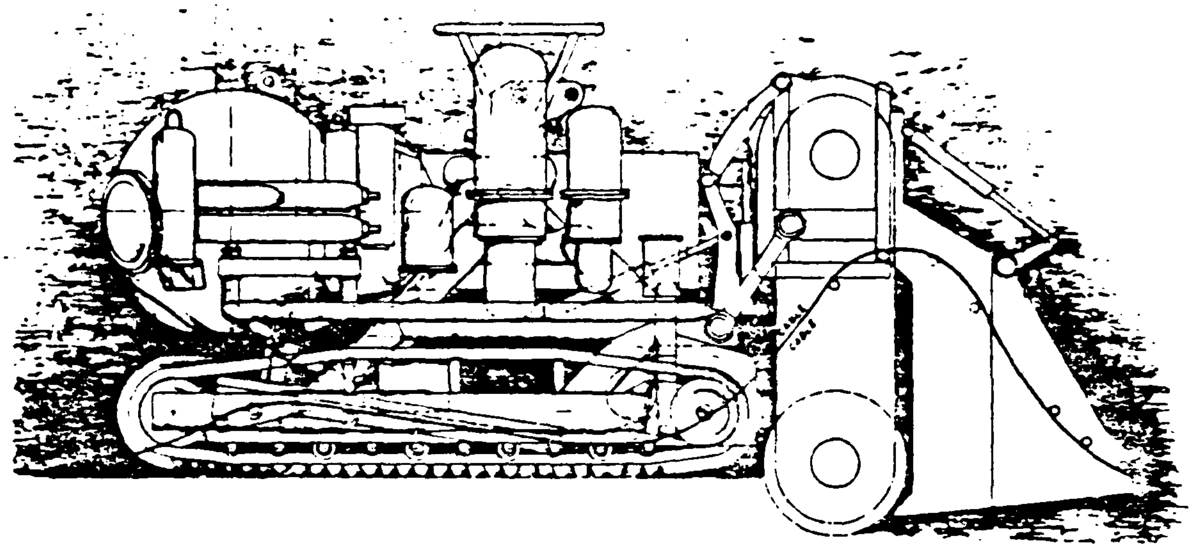


Figure 15. Chambon subsea cable trencher. (From Michel and Pons 1980.)

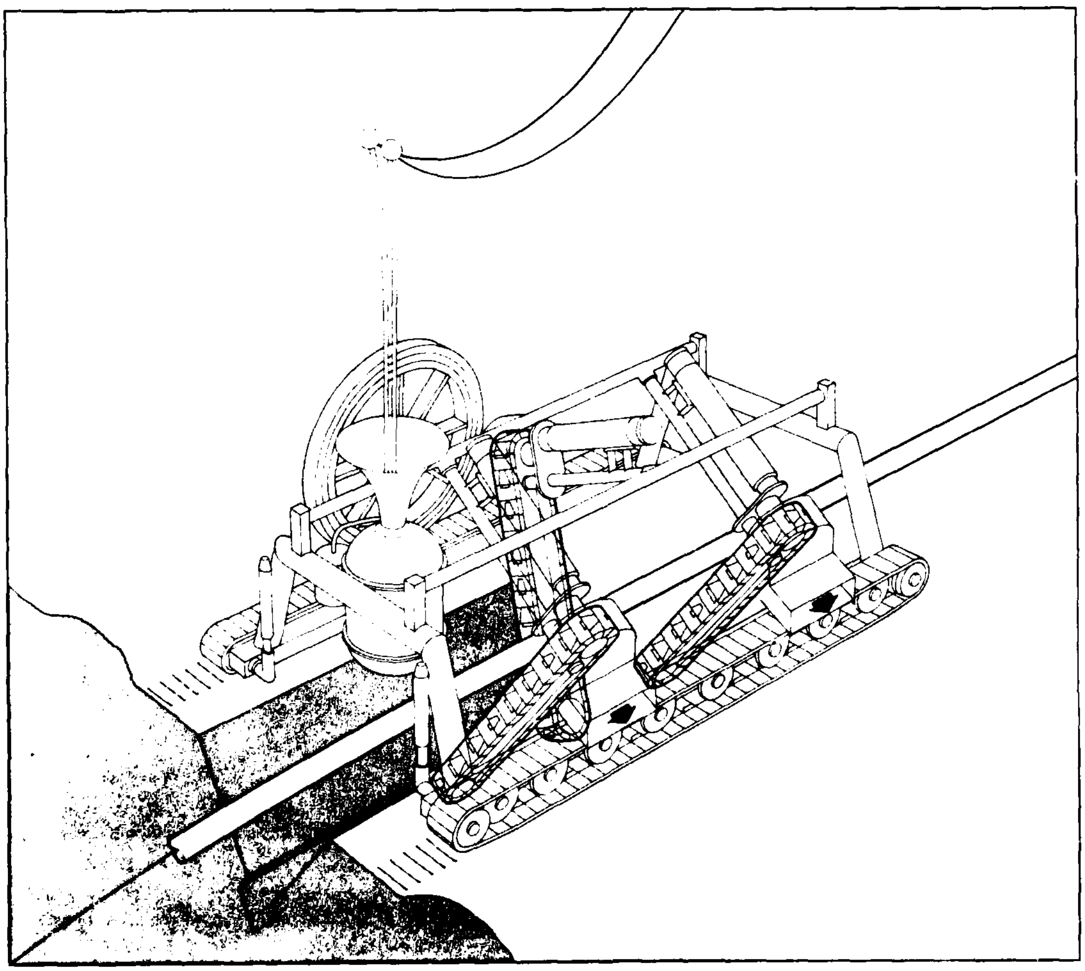


Figure 16. Heerema Eager Beaver pipeline trencher.

ft) (Michel and Pons 1980). The vehicle is controlled by two divers, who occupy an atmospheric pressure command module, entering and leaving though a lock in water depths up to 50 m (164 ft). The machine weighs 33 tonnes (36 tons) in air, and 25 tonnes (28 tons) submerged.

A much bigger machine, the Eager Beaver, has been built by Heerema for digging broad pipeline trenches of trapezoidal cross section in soft sediments and hard clays (Fig. 16). This vehicle weighs 73 tonnes (80 tons) in air, and up to 40 tonnes (44 tons) submerged. It is 12 m (39.4 ft) long, 7.5 to 8.0 m (24.6 to 26.2 ft) wide, and 5 m (16.4 ft) or 7 m (23 ft) high, depending on how much of the overhead gear is rigged. The range of operating depths is 6 to 200+ m (20 to 660+ ft). The crawler tracks are unusual in that they are the relatively flexible and compliant military type (extended Leopard tank tracks) instead of the typical stiff tracks of construction machines. The effective track pressure is 0.25 to 0.35 kgf/cm^2 (3.6 to 5.0 lbf/in.^{2}). Each of the three digging chains is driven by a 225-kW (302-hp) motor with maximum torque of 1760 N-m (1300 lbf-ft). The cutters can trench to a maximum depth of 2.5 m (8.2 ft) at speeds up to 3 m/min (10 ft/min). They have been proved on soils with cohesion (c) up to 110 kPa (16 lbf/in.^{2}). The vehicle's total power demand of 1000 kW is supplied by umbilical from a pair of surface generators rated at 1400 kW total.

SUBSEA ROUTERS AND SLOT MILLERS

Bottom-traveling cutterhead dredges of the fixed-cut type are likely to have the rotation axes of their cutters close to vertical, so that they operate like routers or slot millers. In principle, the same mode of operation can be applied for trenching in rock, and it is understood that Land and Marine Engineering Ltd. is developing just such a milling cutter for use in hard rock. The cutting forces on a router or slot-miller produce a reaction that has a strong side component, and if static reaction from the subsea vehicle is limited, it is desirable to balance out side reactions by using pairs of cutters rotating in opposite directions.

BUCKET LADDER DREDGES

A bucket ladder dredge is similar in some ways to a bucket-chain soil trencher. The vessel is equipped with a boom, or ladder, which can pivot and slide in such a way that ladder angle and digging depth can vary independently to some extent. In the usual configuration, a chain of buckets descends empty along the lower side of the inclined ladder, and returns full along the upper side of the inclined ladder (Fig. 17). Each bucket bites into the work as it passes around the lower tumbler, and dumps its load into the hull as it tips over the upper tumbler. Ladder dredges are usually rated in terms of the capacity of a single bucket, in the range 0.14 to 1.4+ m^3 (5 to 50+ ft^3). Maximum chain speeds are in the range of 20 to 30 buckets/min, with speed tending to decrease as bucket capacity increases. Operating speed depends on the material being dug, dropping to about 10 buckets/min in stiff clay and other tough materials. The power needed to run a ladder seems to be of the order of 30 hp per cubic foot of individual bucket capacity on moderately high-powered dredges with 20 to 25 bucket/min chain speed. Maximum operating depths are commonly 12 to 23 m (40 to 75 ft), but ladder dredges have reached depths up to 53 m (175 ft).

Ladder dredges have not been used for trenching (to my knowledge), and they are sometimes regarded as antiques. Nevertheless, they might be worth considering for work in the relatively shallow waters of the western Arctic, where bottom roughness could conceivably be troublesome for seabed vehicles. A conventional ladder dredge might be modified by reversing the travel direction of the buckets, and then operating "backwards" with the angled ladder trailing instead of "poking." This would make the ladder similar to that of a conventional bucket-chain soil trencher.

VIBRATORY AND PERCUSSIVE DEVICES

For trenching and ripping on land, a variety of repetitive-impulse devices have been tested or considered. The general idea is to oscillate a ripping or plowing tool, or alternatively to modulate the cutting force by applying repeated blows. The intended mode of action varies with the material that is to be penetrated. In soft or thixotropic sediments saturated by water, the idea is to fluidize the material, and hence permit penetration. In rock, the idea is to increase peak cutting forces by percussion, i.e., using inertial forces to exceed the limits for quasi-static force. The devices which are potentially useful in cutting, drilling and penetrating soils and rock can be grouped on the basis of frequency and blow en[illegible] which are inversely related for units of equal power (power is given by the product of frequency, force and amplitude). High-frequency vibrators reach 100 Hz or more, but the blow energy of typical units is 20 ft-lbf or

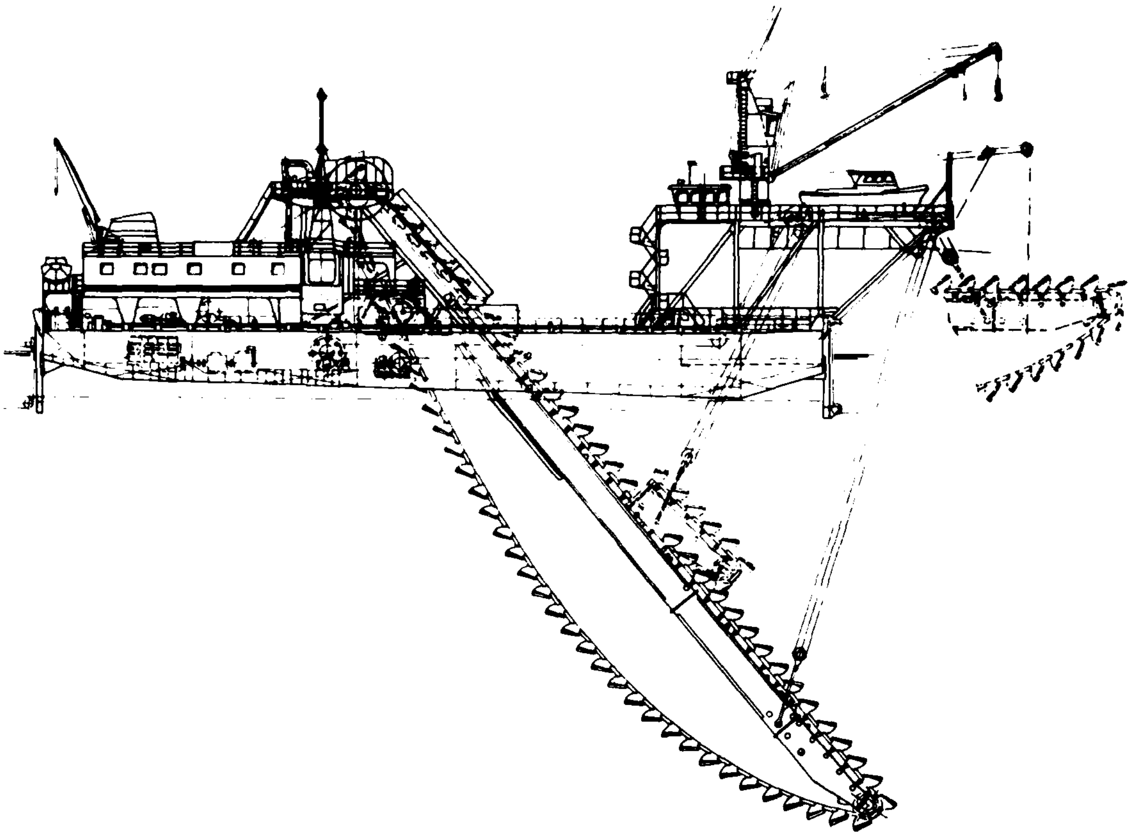


Figure 17. Bucket dredger.

less. Mid-frequency devices, such as percussive drills and small impact breakers, have frequencies of the order of 10 Hz, and blow energies in the range 100–1000 ft-lbf. Low-frequency machines, such as large impact breakers and piling hammers, have frequencies of the order of 1 Hz, with blow energies of the order of 10,000 ft-lbf or more.

Oscillating plows, designed mainly for cable burial, have been in existence for many years. Impact rippers for hard ground have been under consideration or development for at least two decades, but they have not yet appeared in routine service. High-frequency vibratory plows have been proposed, but do not seem to have found favor so far.

For underwater applications, an oscillating plow has been developed by the U.S. Navy Civil Engineering Laboratory, and performance is said to be encouraging. A high-frequency vibrator has been tested on the Harmstorf plow (which also has water jets), but it is believed that it was not particularly successful.

A great deal of development effort has been given to repetitive-impulse plows and rippers over a long period, without conspicuous success. Any group contemplating use of such things for serious subsea trenching should approach the matter very cautiously.

HARD ROCK EXCAVATION UNDER WATER

On land, hard rock trenching usually involves drilling and blasting. Machines fitted with carbide or diamond tools are certainly capable of cutting hard rock, but tool wear and tool breakage make machine cutting too expensive. Costs can be reduced by cutting only narrow kerfs at the edges of the trench and then breaking out the uncut rib, but so far this procedure has not found much favor. For underwater trenching in hard rock, tool wear is not likely to be much different from tool wear in air, but the overall economics of underwater operation are very different from the economics of trenching on land. A subsea machine is more costly than its dry-land equivalent, and the cost of the "surface spread" of support vessels is much higher than the operating cost of the subsea machine itself. Thus tool costs may become quite insignificant, provided that worn tools can be replaced quickly and easily.

While machine cutting of hard rock may turn out to be attractive under water, blasting is likely to remain a preferred technique for the near future. The real problem in underwater work is shothole drilling, and for this reason shaped charges have been widely used. A large frame is loaded at the surface with appropriately spaced shaped charges; it is lowered to the seabed, positioned on the trench line, and its charges are then detonated. The debris is cleaned out from the trench in a separate operation. For trenches that have to be deep and steep, drilling and blasting is likely to do a better job than shaped charges. In shallow water, conventional percussive drills on jumbos can operate from barges, but underwater operation of pneumatic or hydraulic percussive drills has only been tried on a limited scale. For large-scale rock trenching in moderately deep water, it is possible that large work frames, perhaps with walking capability, will be developed to permit underwater drilling and other operations.

CONTROL AND MONITORING OF SUBSEA MACHINES

Most of the modern subsea trenching machines are controlled and monitored from the surface after initial setup by divers. The seabed unit is fitted with sensors, transducers and cameras, which telemeter information via the umbilical to a surface computer and display unit. Video displays may include pictures and graphic presentations of machine attitude and progress. There is usually provision for direct manual control, and for computer control in the fully automatic mode or the supervisory mode. The only significant exception to this trend is the French practice of direct control by divers riding on the subsea unit, either directly exposed to the water or in a capsule.

VESSELS AND VEHICLES

Subsea trenching equipment can be attached to various types of vehicles and vessels.

1. *Sleds or skis.* These are suitable for towed equipment operating on smooth sedimentary seabeds. Dead weight bearing pressure, and hence sliding friction, can be adjusted by buoyancy control.
2. *Towed seabed carriages.* Wheels, rollers or tracks can be used, although only rollers seem to be in use at present. Steel rollers are attractive because of large bearing area and ability to double as buoyancy control tanks.
3. *Self-propelled seabed vehicles.* Although one or two small wheeled vehicles have been built for seabed work (not trenching), crawler tractors are really the only choice. Most machines are two-track vehicles using the conventional stiff, low speed tracks of construction equipment. Track power, based on gross weight of the machine in air, is in the range 0.5 to 2.0 hp/ton, and maximum crawl speeds are 6–9 m/min (20–30 ft/min). Track running around a closed pontoon may be attractive for compact buoyancy control. Flexible military tracks have also been used. For work over very rough bottom terrain, multi-track configurations, including triangular arrays, have been considered, and two-unit articulated vehicles have been proposed.
4. *Seabed work frames.* A multi-gantry frame can be lowered to the seabed to provide overhead support for a trenching device, which can operate from a track in the same manner as a factory crane. This is one way of coping with very rough bottom terrain. Frames can be moved by lift from a surface vessel, by buoyancy and thrusters, or by walking.
5. *Free-swimming submersibles.* Submersibles are sometimes used for carrying and manipulating jetting tools, but with near-neutral buoyancy they are unsuitable for carrying trenching devices that require high static forces.
6. *Surface vessels.* Suction dredges, cutterhead dredges, and bucket ladder dredges are usually special-purpose vessels built around the dredging equipment. Some can carry large volumes of dredge spoil, which is probably a disadvantage for arctic trenching. Tugs or icebreakers, which develop high thrust, can be used for towing some plows. General-purpose barges and pontoons can be fitted with booms for drawing trenching devices along the bottom in shallow waters. Special "bury barges" are used to carry high-power jetting equipment. In U.S. waters, the Jones Act bars foreign vessels.
7. *Surface platforms.* Walking platforms can be used to carry very large cutterhead dredges (Fig. 18), and presumably trenching equipment could be operated from platforms. Barges with deep spuds and jack-up pontoons are similar to platforms.

Most seabed vehicles can be given some underwater maneuvering capability by buoyancy control and thrusters. Most also need a surface support vessel with appropriate lifting capability,

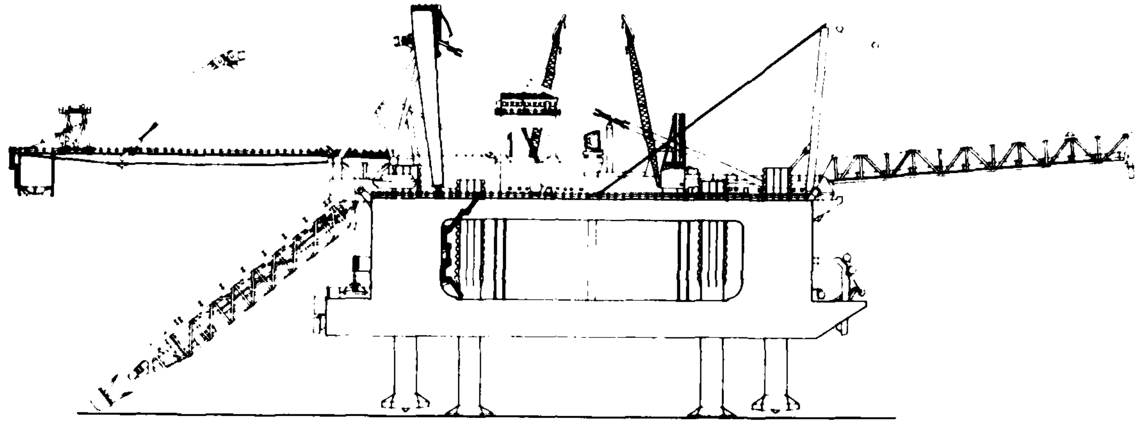


Figure 18. A walking semi-submersible platform carrying a large CS dredge unit. Range of working depths 6.5 to 32 m (21 to 105 ft). Cutter power 5000 hp. Total installed power 35,000 hp. Pipe diameters 1.1/1.0 m (43/39 in.) (Royal Volker Stevin).

which means a very big A-frame for machines weighing over 100 tons.

TRENCHING FROM THE SEA ICE

As an alternative to open-water operations with expensive surface vessels, it would be possible to work from the fast ice where local conditions are favorable. The first requirement is sufficient ice thickness to support the equipment, and this limits the working period to winter and spring, with mid-winter least desirable because of darkness and severe weather. An ice road would probably be required, calling for snow clearance and for ice excavation through pressure ridges, old floes, and rough ice in general. Cutting and maintaining a slot through the ice is not difficult technically, but it could be troublesome operationally in winter.

Through the shallows there is insufficient clearance between the ice and the seabed for a seabed machine to work, and it would probably be advantageous to dig with "dry" machines that sit on the ice. Backhoes, draglines and clam buckets are possibilities, but a ditcher with a long bucket ladder (or long saw) might be better.

When the clearance between the ice and the seabed is sufficient, it becomes possible, in principle, to operate a seabed machine, using access and exit holes and a relatively narrow slot between them to permit passage of the umbilical, and also a tow cable for machines that are not self-propelled. However, existing subsea crawlers are typically 4 to 7 m (13 to 23 ft) high, and the keels of old floes trapped in the fast ice can easily project several metres below sea level. Thus, in the western Arctic there could be wide areas where the water is too deep for ordinary machines to reach down from the surface, but not deep enough to operate under the ice. One solution would be to cut and clear a wide channel through the thick ice and pressure ridges, but this could get expensive and detract from the advantages of working on the ice.

Near and beyond the outer limit of the fast ice there is no possibility of trenching from the ice because of ice movement, fracturing, rafting, ridge formation, and enormous shear ridges.

COSTS OF SUBSEA TRENCHING

At this stage it is virtually impossible to estimate costs for an undefined project in an unspecified location in the Arctic. For self-propelled seabed crawlers and their associated equipment, construction costs at present-day prices might be in the range $19 to $63/lb, or $2500 to $7500/hp, depending on machine characteristics, and on how much of the development cost is included. A towed seabed unit with remote control of functions and a small amount of onboard power might cost on the order of $10/lb. Daily operating cost for a seabed machine and its surface support would almost certainly exceed $100,000 in the Arctic, with perhaps 15 to 20% of the total cost chargeable against the subsea unit itself. The operating cost for a fairly conventional self-contained dredge vessel might be significantly lower. The unit cost of trench is even harder to estimate but, to start the bidding with a wild guess, it is unlikely to be less than $200/m, even in shallow water and relatively soft bottom. Off Labrador and Newfoundland, in water depths of 100 m or more, the unit cost could easily be an order of magnitude higher for trenches in "cuttable" rock. As the technology develops, it is conceivable that real costs (adjusted for inflation) could decrease.

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APPENDIX. DESCRIPTION OF WATERS OFF ALASKA AND NEWFOUNDLAND

THE COASTLINE OF ALASKA

Alaskan coasts southeast of the Aleutians are subject to ice problems, but not severe ones. Sea ice forms in sheltered embayments and there is undoubtedly some small-scale ice gouging of the bed sediments, but this probably does not constitute a major hazard, except at particularly unfavorable sites. There are tide-water glaciers calving into the sea, but none of them produce icebergs comparable to Greenland icebergs. Even the Columbia Glacier, which is expected to calve profusely when its terminus retreats from shoals into deeper water, is unlikely to produce large icebergs. There is no underwater permafrost, and only seasonal freezing of soils along the shoreline. The geology and oceanography of the Kodiak Shelf are described by Peterson (1980) and Sobey (1980).

North of the Aleutians, the climate and the ice conditions become progressively more severe, while seismicity and tsunamis are factors in construction planning. Shoreline soils are subject to discontinuous permafrost conditions or to deep seasonal freezing, and coastal erosion is considerable in some areas. There is probably little ice-bonded permafrost beneath the sea. The Bering Sea, with its very broad, flat continental shelf, is subject to severe ice conditions, with much disruption and ice motion caused by winds, waves and currents, by strong and complex tides, and by storm surges. Ice gouging of the bed sediments is likely to be widespread, but so far little information is available except for Norton Sound. Ice thrusting and piling on beaches and shores can also be severe. At Fairway Rock in the Bering Strait, cables have been damaged systematically by grounding pressure ridges (Bloom and McDougal 1967). Maximum gouge depth in the area was thought to be about 4.6 m, while gouging was thought to be most active in water 6 to 24 m deep.

The coast of the Chukchi Sea, trending northwest from the Bering Strait to Point Barrow, represents arctic conditions. Permafrost exists on shore, and also under the continental shelf. The sea is covered by ice for much of the year, and ice gouging of the seabed is probably widespread and quite severe.

East of Point Barrow the extreme northern coast of Alaska faces the Beaufort Sea, which extends eastward into Canada and across Mackenzie Bay. Coastal waters are covered by ice for much of the year, and bed sediments are heavily gouged by ice over most of the continental shelf above the 50-m isobath. On land, the almost featureless tundra is underlain by permafrost, and permafrost extends out under the continental shelf.

BEAUFORT SEA COAST

The present coastline is formed by active transgression of the sea and erosion of the flat-lying Arctic Coastal Plain. There are deep embayments, river estuaries, and deltas, but offshore chains of barrier islands enclose shallow lagoons and tend to straighten out the margins along some stretches. Active coastal erosion and sedimentation arise from thawing of coastal permafrost, from wave, current and ice action, and from sediment deposition and transport within and around river deltas. Barrier islands, and the passes between them, migrate westward quite rapidly (metres, or even tens of metres, per year), and coastal bluffs erode seasonally at rates ranging from about 1 m/yr to more than 10 m/yr, depending on soil type and erosion processes. Beaches are typically narrow, with eroding backshore bluffs or banks.

Open water exists, and wave action occurs, from midsummer until late September or early October. During this period beaches thaw to a depth of 1.5 m or more. Shallow inshore waters are not subject to strong wave action, especially where shelter is provided by the barrier islands. In deeper water outside the barrier islands, wave development is controlled partly by proximity of the pack ice. Astronomical tides are weak, with mean tidal range about 0.1 to 0.3 m. Nearshore currents flow to the west on the east side of Point Barrow, and in a northeasterly direction on the west side of Point Barrow. The greatest variations in sea level in the Beaufort are caused by open-water storm surges, with positive surges raising the level by up to 3 m at the coast. Both positive and negative surges also occur when the sea is ice-covered, but the change of level is usually smaller (1 m or less).

Water salinity varies greatly with location and season due to flows of rivers and meltwater, and to melting and freezing of sea ice. It is generally less than open-ocean salinity, with about 25‰ a representative value for coastal water remote from major rivers. Sea surface temperature in August can be a few degrees C above freezing, depending on location. Since temperature is more or less constant, water density varies in much the same way as salinity.

New sea ice begins to form as a continuous sheet along the coast in early October, and it continues to grow until the end of March or later, by which time the thickness is about 2 m or perhaps slightly more. Close to shore (say out to 20 m depth) the annual growth of ice (plus trapped "old ice") remains in place and is known as "fast ice," or "landfast ice." Although more or less fixed in place, it is subject to occasional fracture, disturbance, and thrusting. In very shallow water (up to 2 m deep) it is grounded, and thus the bottom sediments are subjected to relatively low temperatures. Far out beyond the fast ice (100 to 200 km from shore) is the drifting polar pack ice, which consists largely of thick and irregular multi-year floes, partly separated by open water and thin ice during the summer, and by "first-year" ice in the winter. Between the polar pack ice and the fast ice is a transitional zone where the seasonal ice cover breaks up to form pack ice, and where there is shearing between the immobile fast ice and the moving pack ice, which follows an overall clockwise circulation in the Beaufort Gyre. In winter, the polar pack ice is generally over the deep water beyond the continental shelf, while the transition zone, of the order of 50 km wide, is roughly along the break of the continental shelf. However, ice conditions can vary considerably from year to year.

The sea ice is subjected to wind shear on its upper surface, and water shear from currents on its lower surface. High stresses can develop in the ice sheet, leading to overthrusting (rafting) and to formation of "pressure ridges," either by compressive stress alone or by combination of compression and shear. The main bulk of a pressure ridge is below water level, and the ratio of keel depth to visible ridge height (draft/sail ratio) is typically about 5, with extremes of perhaps 3 to 9. Free-floating ridges can have keels reaching down to 50 m or more. When ice is thrust against the shoreline it can ride up the beach, or build up large mounds and ridges of ice debris that may exceed 10 m in height. While the ice "pile-up" tends to develop within about 10 m of the water's edge, an ice "ride-up" can push 50 to 100 m inland. In either case, the ice can bulldoze sediments or damage structures near the shoreline.

The continental shelf of the Beaufort Sea is typically flat, with average slope 5×10^{-4} (0.5 m/km) and maximum slope 1.3×10^{-3} (1.3 m/km). The edge of the shelf occurs at a depth of 50–70 m, and the width of the shelf is in the range 76–97 km in the western parts and 40–48 km in the eastern parts. Beyond the shelf there is very deep water (almost 4000 m). Migrating offshore bars extend en echelon to a distance of about 0.5 km seaward. There are some submerged ridges, and in three places the shelf is crossed by submarine canyons. The most widespread small-scale features are gouges in the bed sediments created by the keels of moving ice ridges. The gouges range from very shallow grooves less than 1 m deep to troughs about 8 m deep. They tend to be aligned more or less parallel to the coast, and their lengths vary, from around 10 m to as much as 10 km. The gouges, which have raised lips along their edges, range in width from about 1 m for very shallow grooves to more than 100 m for overlapping multiple grooves or for gouges made by large ice masses.

Overconsolidated clays and silts are common at the seabed, and there is an incomplete veneer of loose mud or sand, ranging in thickness from zero to a few metres. Off the major river estuaries and around the barrier islands there may be sand or gravel. Under water less than about 2 m deep, the sediments are subject to seasonal freezing. In deeper water, seabed temperatures below 0°C are common, but freezing of the sediments is rare because the pore water is saline. In some areas of deeper water there may be partial bonding of sediments by seasonal freezing, but the resultant changes in strength are minor. Ice-bonded permafrost does exist beneath the continental shelf, but its upper surface is usually well below the seabed. In very shallow water close to land or islands, the top of permafrost may be only a few metres below the seabed, but in deeper water it is likely to be 30 m or more below the seabed, or even in excess of 100 m below the bed.

Mechanical properties of the bed sediments are not yet well known, and they vary considerably from one place to another. However, some preliminary generalizations may be useful. In the overconsolidated fine-grained sediments likely to be encountered in trenching, soil strength will probably be greater than the strength of typical sediments in non-polar areas. In sampling work by Sellmann and Chamberlain (1979), the shear strength of sediments within 2 or 3 metres of the seabed ranged from less than 35 kPa (5 lbf/in.^{2}) to about 85 kPa (12 lbf/in.^{2}). For the deeper layers, shear strength ranged up to about 260 kPa (38 lbf/in.^{2}). These values are higher than some earlier indirect estimates of about 20 kPa (3 lbf/in.^{2}) for unconsolidated sediments in the Beaufort Sea (Kovacs and Mellor 1974). Penetrometer measurements have also been made (Blouin et al. 1979, Sellmann and Chamberlain 1979), but it is difficult to interpret the values of apparent penetration resistance in terms of shear strength or uniaxial failure stress. These data are best used for comparing the strengths of materials in vertical sections, or across long horizontal profiles of the bed.

CHUKCHI SEA COAST

The coast of the Chukchi Sea has much in common with that of the Beaufort Sea, especially with regard to factors that could affect the laying and maintenance of pipes and cables. However, there are differences in coastal morphology, ocean currents, sediment transport, general stability, and overall sea conditions.

The northern and northwestern coastline of the Chukchi Sea, west of Point Barrow, is in some stretches exposed to wave erosion and shallow river deltas. The westerly projection of the coast between Cape Lisburne and Cape Thompson generally has eroding rocky sea cliffs, but Point Hope is a depositional feature. South of Cape Thompson the coast is erosional, mainly with narrow beaches and low cliffs; along some stretches there are lagoons and barrier beaches. Kotzebue Sound has shallow water, with a delta shore on the east and low hills to the south. The north-facing coast from Kotzebue Sound to Cape Prince of Wales is depositional, with barrier islands and lagoons. The main sediment transport is apparently material from the Yukon River carried north through the Bering Strait.

Wave erosion and sediment transport virtually cease during the 9-month freezing period each year. Long and deep snowdrifts form in the lee of suitably oriented coastal bluffs, covering the beach area. In summer, beaches thaw to a depth of 1.5 to 3 m, and there can be major erosion of cliffs and very active deposition (e.g. Point Hope is migrating south at about 3 m/yr). During the open water period in summer, wave action is generally greater than in the Beaufort Sea, with local winds driving waves (usually less than 5 m) mainly from the north and northwest. The main open ocean current flows north through the Bering Strait, following the general trend of the coastline until it is eventually swept around into the clockwise gyre of the Arctic Ocean near Point Barrow. The inshore currents are complex, variable and generally weak. The tide is semi-diurnal, with a range of about 0.3 m, except in shallow bays where it may be 0.6 to 0.8 m. Bigger changes in water level are brought about by storm surges, which can raise the level by as much as 3 m during the open-water period.

Ice-free water along the Alaskan coast of the Chukchi Sea is relatively warm—up to 10°C or so near shore. Temperature decreases to the west, and to the north. Salinity varies with location and season, largely under the influence of river outflow, freezing and thawing of the ice, and mixing conditions. In waters close to shore, salinity is commonly less than 30‰.

Coastal waters freeze in fall or early winter, depending on location. The average date of freeze-up for various locations typically ranges from early October to late November. The date of ice breakup is similarly variable with location, average dates ranging from late May to late June. The coastal fringe of fast ice and immobile broken ice varies in width from place to place and with the seasons, but during winter it is typically tens of kilometres wide. The width of the fast ice tends to be least around exposed capes and headlands, and greatest in protected embayments and shoal waters. Beyond the fast ice there is the shear zone, and then the moving pack ice. Pressure ridges form both in the fast ice zone and in the moving pack ice. Ice piling and shear ridge formation occur in the vicinity of small islands and shoals. There is much movement and disruption of ice in the Chukchi Sea, under the influence of the northerly offshore current flowing out of the Bering Strait, and also by wind-driven inshore flows that vary in direction with location and wind direction.

The Chukchi Sea has a broad, flat continental shelf, but along the Alaskan coast the slopes, although gentle, are somewhat steeper than those along the edge of the Beaufort Sea, with gradients up to about 3×10^{-3} (3 m/km). The shelf in this area is cut by several valleys or canyons. The waters are shallow throughout the Chukchi Sea, and within 50 to 100 km of the Alaskan coast the depth is typically around 40 m.

With a shallow continental shelf, soft bottom sediments, and very active pressuring and movement of heavy ice, widespread ice gouging is inevitable. However, because of the periodic transport and deposition of large quantities of sediment, it is quite possible that gouges fill in fairly rapidly.

The most systematic study of ice gouging in the Chukchi Sea (Toimil 1979) covers a range of water depths from 20 to 70 m, although other observations have confirmed that there are gouges in shallower water. Statistical analysis indicates that gouges in the Chukchi become more frequent as latitude increases, as bed slope increases, and as water depth decreases. The number of gouges intersected by a transect at right angles to their direction can exceed 200 per km. The deepest gouging was found in water 36 to 50 m deep, with the maximum gouge depth of 4.5 m in the 35- to 40-m depth interval. Present-day gouging is believed to occur to a water depth of at least 43 m. However, the total number of gouges drops off in the deeper water. Beyond the 56-m isobath there were less than 10/km, and between 58 and 70 m no gouges were detected. The widest gouges also occur in moderately deep water. The broadest, over 100 m wide, were found in the same depth range (36–40 m) as the deepest gouges.

Current-induced sediment bedforms were found cutting across gouges, and vice versa, so that there is not much doubt that gouging is a contemporary process.

We have not yet come across any data on the mechanical properties of bed materials in the Chukchi Sea, but some general speculations can be made. Bedrock is expected to be closer to the seabed than in the Beaufort because of greater stability of the coastline. Sediment transport and deposition may be more active than in the Beaufort, perhaps giving greater coverage of low-strength loose sediments over the bed. Occurrence of high-strength overconsolidated sediments may be less widespread than in the Beaufort.

THE COAST OF LABRADOR

The coasts of Newfoundland Island and Labrador are very different from the northern Alaskan coasts. On land, there is much exposed bedrock, considerable relief and high vegetation where soils exist. There are numerous lakes and small rivers, distinct hills and valleys, and general features of a glaciated landscape. The coastal climate is harsh and windy, but not excessively severe, in the south (mean annual temperature about +5 °C); it deteriorates to an arctic climate in the north (mean annual temperature about -5 °C).

The coastline generally is rugged and indented, with numerous deep-water bays and inlets, rocky headlands, and rocky islands. The whole region was eroded and sculptured by the Pleistocene ice sheet, and in post-glacial times the balance between sea level rise and isostatic rebound has resulted in net submergence of the coast. The inshore areas of the continental shelf are rocky and irregular, with submerged glaciated terrain. Beyond this coastal zone there is a discontinuous margin channel running parallel to the coast, and further out the main shelf, which consists of a series of flat-topped banks. The outer margin of the shelf is taken as the 500-m isobath, which lies between about 100 and 300 km from the coast. The tops of the banks are about 200 m deep, while the "saddles" running between them are 300 to 400 m deep. The north–south extent of the shelf is from about 60 °N down to about 52 °N.

Glaciers of the Quaternary ice sheet probably extended to the edge of the continental shelf, eroding deep channels where the saddles between the banks now lie, and generally sculpturing the bottom relief. Thick deposits of glacial drift were laid down, with debris transported largely from the land as moraine, as meltwater sediment, and perhaps as iceberg-rafted debris. The glacial deposits range from clay and silt, through sand and gravel, to large cobbles and boulders. Figure 2 gives an idea of the thickness of the glacial drift. Mud tends to accumulate in deep water zones on the shelf.

The main open-ocean current on the continental shelf is the Labrador Current, flowing southerly in a direction parallel to the general trend of the coast. It is fed from the cold Baffin Land Current, which tends to form the landward side of the Labrador Current, and from a westerly and southerly return loop of the relatively warm West Greenland Current. The latter component tends to stay on the offshore flank of the Labrador Current.

Sheltered embayments and inlets along the Labrador coast usually freeze over in November, and remain ice-covered until June, although there are variations from place to place and year to year. The sea ice off shore is mainly arctic pack ice moving down from the north under the influence of wind and current. Ice from Baffin Bay and the Fox Channel reaches the Labrador coast in November, spreading down to Belle Isle Strait by December, eventually blocking the strait and continuing to spread down as far as the northern edge of the Grand Banks by the end of January. Sea ice begins to retreat from the Grand Banks about April, and the waters off the Labrador Coast may clear about July. However, in some years, areas of pack ice can persist throughout the summer.

The sea ice off Labrador does not appear to cause any significant gouging of the seabed, since the moving pack ice is in deep water. However, serious gouges in relatively deep water are produced by icebergs.

Icebergs carried along the Labrador Current originate chiefly in Greenland valley glaciers which calve into the sea in the general vicinity of Melville Bay. Although very large numbers of icebergs are produced by the west Greenland glaciers, only a small proportion of the total reach the Labrador Coast. Table 2 shows the average monthly flux of icebergs for each degree of latitude from

50°N to 61°N. In any one year the flux can vary greatly from the average, and Gustajtis (1979) notes that in 1972 about 1600 icebergs drifted south of 48°N. A recent report in *Ocean Industry* (April 1981) gives the number of bergs passing through the Hibernia area as 1400 in 1974 (a record), 1200 in 1978, 400 in 1979, and zero in 1980. An idea of the size distribution of the icebergs at various latitudes is given by Table 3. Icebergs in this region have a wide variety of irregular shapes, and it is not easy to either measure or estimate their drafts. The range of the draft/height ratio, according to both calculations and measurements, is from less than 2 to about 9 or 10, depending on the shape of the iceberg and perhaps on its overall size. From evidence reviewed by Gustajtis (1979), it appears that the typical draft/height ratio may be about 3 ($\pm$ 0.5).

Icebergs have great mass (commonly in excess of a million tons, and up to 15 millon or so), and therefore they possess great kinetic energy even when drifting very slowly. When their keels ground in gently sloping sedimentary bottom materials, they are capable of plowing long furrows, especially when the kinetic energy is supplemented by sustained current drag and thrust from surface sea ice.

Gouging of the seabed is widespread off Labrador and Newfoundland. Significant concentrations of gouges have been detected in water up to 300 m deep, although typical present-day icebergs seem likely to have maximum drafts of about 200 m. In spite of the great difference between icebergs and sea ice pressure ridges, the dimensions of iceberg furrows are not much different from the bigger gouges found on the continental shelf of the Beaufort and Chukchi Seas. Gouge depth reaches several metres, with maximum relief from the bottom of the trench to the top of the laterial berm reaching about 10 m. The gouges are typically tens of metres wide, although very broad ones can be more than 100 m wide. The deepest gouges measured in the Hibernia area are 2 m, and in the Avalon Channel, 5 m. Little is known about the mechanical properties of the bed sediments where gouging occurs, but it has been surmised that shear strength might range from about 1 kPa in loose sediments to 550–2400 kPa in consolidated glacial drift (Gustajtis 1979).

Icebergs in this area pose a serious threat to cables and pipelines. Table 1 gives a list of past cable breaks that are attributed to icebergs grounding in water depths from 77 to 366 m. Gustajtis (1979) also cites a report of an iceberg grounding and damaging equipment in water more than 450 m deep. A proposed cable crossing in the Belle Isle Strait, in 100-m water depths, is subject to gouging, even though there is a 70-m sill up-current. The area averages 66 large bergs per year.

Detailed statistics of the concentrations, size distributions, and occurrence frequencies for iceberg gouges are not yet available, but work on the problem is in progress.

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